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(El documento empieza en la siguiente página)

The Use of Prestressing Through Time as Seismic Retrofitting of Historical Masonry Constructions: Past, Present and Future Perspective

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Abstract. Unreinforced masonry is one of the oldest construction materials and main component of historical buildings. Masonry is a heterogeneous material with an anisotropic behavior and may fail quasi-brittle during earthquakes. This paper describes the main components and arrangements of historical masonry, seismic vulnerability and existing retrofitting techniques, especially prestressing. Based on the evolution of prestressing, it is developed a future perspective about the use of this technique on cultural heritage. Especial attention may be taken into account when using this technique because the compressive strength may be exceeded, leading to an explosive brittle failure. The correct application of prestressing requires the designing of a compatible device and optimal post-tensioning force that improves strength and ductility without endangering the structure.

Key words: prestressing, retrofitting, earthquakes, old masonry, historical constructions, smart materials, fiber reinforced polymers, shape memory alloys.

El uso del presfuerzo a través del tiempo como refuerzo sísmico de construcciones históricas de mampostería: pasado, presente y perspectiva futura

Resumen. Se describen los principales componentes y arreglos de mampostería histórica, vulnerabilidad sísmica y técnicas existentes de refuerzo, principalmente presfuerzo. Tomando como base la evolución del presfuerzo, se presenta una perspectiva futura sobre su uso en la herencia cultural. Se requiere atención especial al usar esta técnica, ya que la resistencia a compresión puede ser excedida, presentando una falla frágil y explosiva. La aplicación correcta requiere el diseño de un dispositivo compatible con fuerza de post-tensionado óptima que mejore resistencia y ductilidad sin dañar la estructura.

Palabras clave: refuerzo sísmico, presfuerzo, mampostería antigua, construcciones históricas, materiales inteligentes, FRPS, SMAS.

Introduction

Unreinforced masonry is one of the oldest constructions materials and it is commonly found in most of historical buildings and monuments all over the world. Masonry is a heterogeneous material with an anisotropic behavior due to the nature of its two main components, units and mortar. Both components have different behavior if analyzed separately, the units are very stiff and the mortar

has a more ductile behavior than units. If analyzed as a composite, masonry behaves in a different way of that of its components, with a behavior in between, not so stiff and not so ductile. In terms of strength, masonry presents an acceptable compressive resistance if compared to its poor tensile strength (almost zero). Due to the lack of tensile strength, heterogeneity of its components and anisotropic behavior, masonry structures (walls, domes, arches, columns, etc.) may fail quasi-brittle in case of earthquake (EQ) action,

presenting different behavior and failure modes in dependency of the direction of the seismic inertia forces. If the seismic loading acts in the plane of the structure, it may present different failure mechanisms such as bending cracks if the element is slender and diagonal shear cracks in case of compact structures. In the case of out-of-plane loading, the common failure mechanisms are represented by overturning of external walls and façades, or the collapse of the roof system into the building as in the case of Cathedrals.

The main objective of this paper is to describe the main components and arrangements of unreinforced masonry as the main construction material of historical buildings, its vulnerability to EQS and existing techniques and materials for the seismic retrofitting, especially prestressing. From an overview based on the evolution of prestressing through time as seismic retrofitting of old structures including conventional and smart materials, it is developed in Section 7 a future perspective about the use of this technique on historical masonry buildings. It has been demonstrated that the level of seismic improvement strongly depends on the level of prestressing force (Sperbeck, 2009 and Preciado, 2011). Especial attention may be taken into account when using this technique in historical masonry structures because the intrinsic compressive strength may be exceeded, leading to an explosive brittle failure of the top anchorage or the base of the structural element. The correct application of prestressing requires the designing of a compatible prestressing device and an optimal prestressing force that accurately improves strength and ductility without endangering the structure to fail by an exceedance of its compressive strength.

1. Unreinforced masonry

Masonry is known as the combination of stones or bricks with a mixture named mortar that binds the construction units together and fills the gaps between them. Unreinforced masonry is one of the main materials commonly found worldwide in ancient buildings. The use of this material as structure goes back to the first civilizations that populated the earth. In Mesopotamia, the ancient cultures used adobe masonry as main construction material in their structures. Adobe is integrated by sun-dried clay bricks placed together with mortar of the same material. On the other hand, in Egypt, carved stone with no mortar between units (named as well masonry of dry joints) was used for the construction of their pyramids. This typology of masonry was widely used in America by the Aztecs in Mexico and the Incas in Peru. Maya culture used for their pyramids and temples carved

stone in combination with mortar made of burnt fragments of lime stone. The Romans in Italy used stones and fired clay bricks combined with enhanced mortars and innovative techniques for the construction of walls, arches, vaults and domes in large structures mainly reinforced by buttresses.

Mortars in ancient structures were mainly made of clay or lime in combination with water. In some cases, other materials or compounds were added to the mortar for increasing its capacity of adherence, resistance, durability and malleability. This is the case of the mortars used by the Romans named pozzolana, which is a normal mortar of lime enhanced with the addition of volcanic ashes. This led to develop the first concrete which had important uses for the construction of aqueducts, bridges and other important structures. On the other hand in America, especially in the constructions of adobe in Mexico, fibers of vegetation, blood of animals and extract of cactus plants were used to enhance the units and clay mortar. This reduced the contraction of the material generated by drying, and improved its resistance to the climate effects. It was until the end of the XIX century when the Portland cement was introduced, obtaining mortars of larger resistances than those of limes, with faster hardening and higher elasticity modulus. The presence of this mortar in old constructions is commonly due to recent rehabilitation measures. SMIE and FICA (1999) indicate that the main properties of mortars are: resistance, adherence with the unit, workability, durability, and impermeability. However, since ancient time, masonry has been widely appreciated around the world by different important factors such as availability, durability, bioclimatic characteristics and low cost.

2. Typologies of masonry used in historical structures

In the construction of historical structures multiple typologies of masonry were used depending on factors such as availability of materials, structural element to be built (wall, buttress vault, dome, or tower), construction technique and appearance. Here, typology refers to the arrangement of masonry (see figure 1). This order or assemblage is the way that units and mortar are placed together to conform the structural element, involving on it different construction techniques. There is a huge variety of construction modalities commonly found in old masonry buildings and may be described in two main groups (Meli, 1998). These correspond to the organized or regular masonry of bricks or carved stone with head and bed joints of mortar (figure 1a), and the disorganized or irregular, where the stones are placed without a complete

carving (or natural) and irregularly distributed in a matrix of mortar (figure 1b). Another combination that could be found in historical constructions is the three-layer masonry, where the external layers have a regular arrangement that works as a falsework for the infill commonly composed of rubble of other constructions mixed with mortar (figures 1c and d). In the work of Croci (1998), the author mentions that six types of masonry have been the most commonly used in the construction of old structures. These mainly correspond to bricks of fired clay or carved stones with regular mortar joints; natural stones of different types and shapes; sack masonry; combined masonry, made of stone and bricks; masonry of dry joints (no mortar between units), composed by rectangular pieces of carved stone; and bricks of sun-dried clay (adobe) with mortar of the same material.

3. Seismic retrofitting of historical masonry structures

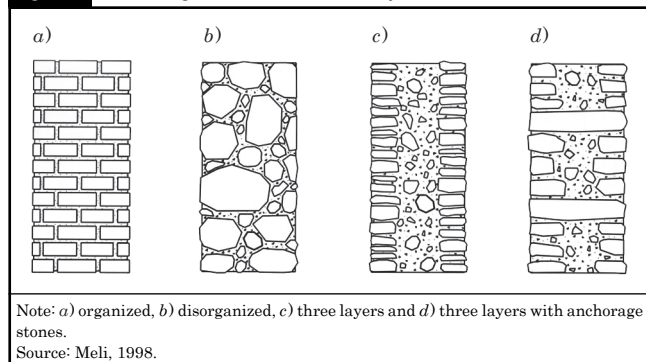
During EQS masonry structures are highly vulnerable to suffer partial or total collapse due to the poor tensile strength of their materials. The risk management of existing buildings located in EQ prone zones is integrated by two huge stages, the risk assessment and its reduction. There is an enormous number of methods to assess the seismic risk of buildings (Carreño *et al.*, 2012), but there is a large confusion within the scientific community regarding the procedure to follow for assessing this risk and the measures to take for its reduction. Recent studies in EQ engineering are oriented to the development, validation and application of techniques to assess the seismic vulnerability of existing buildings (Carreño *et al.*, 2007, Barbat *et al.*, 2008, Lantada *et al.*, 2009 and Pujades, 2012). Assessing the seismic vulnerability of a historical building is a complex task if compared to other existing or new building as explained in the works of Barbieri *et al.* (2013); Foraboschi (2013); Preciado and Orduña (2014) and Preciado *et al.* (2014, 2015). Nowadays, there

is a large variety of techniques and materials available for the protection of historical masonry constructions. Among them, two main techniques are distinguished: the rehabilitation (or restoration) and retrofitting. Rehabilitation uses materials of similar characteristics to the original ones and applies the same construction techniques, in order to locally correct the damage of structural elements. In general terms, the objective of these works is to preserve the building in good conditions and in its original state, mainly to withstand the vertical loading generated by self weight (dead load). On the other hand, structural retrofitting intends to use modern techniques and advanced materials in order to improve the seismic performance of the building, by increasing its ultimate lateral load capacity (strength), ductility and energy dissipation. Compatibility, durability and reversibility (removability) are the fundamental aspects recommended in literature to be taken into account when retrofitting is used for the seismic protection of cultural heritage. A good compatibility of deformations between materials is important in order to avoid a stress concentration that could generate damage to the rest of the structure. The durability of some retrofitting materials is not so easy to determine due to the lack of capability verification to keep their mechanical properties and durability for centuries. Reversible retrofitting has the capability of being removable and is definitely the most important aspect when modern techniques and materials are implemented in the seismic strengthening of ancient buildings. If the applied technique is not suitable or when there is a new material or technique that allows a better seismic performance, this old intervention could be substituted.

4. Prestressed masonry structures: past and present

Prestressing consists of the application of a compressive force to masonry elements and may be achieved by post-tensioning high resistance steel tendons. The selection of the appropriate technique and materials depends on every case study and the purpose of the intervention. In the following paragraphs an overview based on the evolution of prestressing as seismic retrofitting of historical masonry structures is described. Prestressing of masonry structures is not a recent retrofitting technique as can be observed quite often in existing ancient masonry buildings in Italy (see figures 2 and 3). Past interventions were developed in the Roman Coliseum at the beginning of the XIX century to connect the internal walls perpendicularly located to the external ring (figure 2a), in order

Figure 1. Four arrangements of ancient masonry.

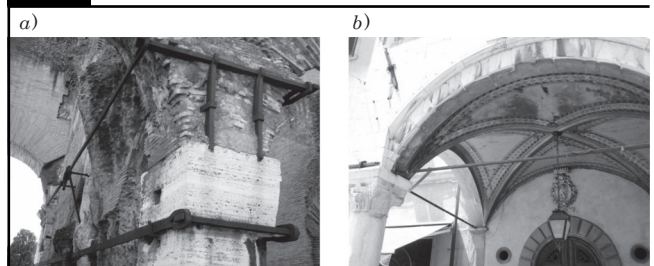


to protect them against out-of-plane loading that could cause overturning (Croci and D' Ayala, 1993 and Croci, 1998). The addition of different types of metal bars was a common practice in past interventions of old constructions. Figure 3 shows several types of metal bars with their anchorages and tighteners of the same material. In order to generate the effect of prestressing the metal tie was usually heated to expand the material and when it returned to its normal temperature by means of the contraction, a shortening was generated, producing the active prestressing force. Through the history, the most frequent uses of old prestressing in ancient structures have been to tight and to connect walls to prevent overturning and to stabilize arches, vaults and cupolas that were damaged or identified as instable by opening or movement of their supports due to seismic forces (figure 2). The main disadvantages of these old metal bars are their heavy weight and the susceptibility of the material to corrode, reducing its resistance and damaging masonry by the volumetric change of the corroded bars. Moreover, the difficulties to generate a good connection between bars and the excessive concentration of stresses induced by the anchorage to the masonry could lead to crushing. Another disadvantage was that there was no control or monitoring of the prestressing force, changing throughout the years by temperature, corrosion and by relaxation due to deformation of masonry (creep).

Modern prestressing had its principles at the beginning of the xx century with the development of prestressed concrete structures. The adaptation of this technique to the seismic protection of historical constructions has reached in recent decades particular interest for many researchers around the world and has been a topic of very active research. In prestressing, the compressive force generates a distribution of compressive stresses that compensates the tensile strength of masonry and structural stability at key locations identified in the seismic vulnerability evaluation (see figure 4). With the recent technological advances in drilling equipment and high resistance tendons of small diameters and low weight, it is possible to apply prestressing in old constructions though holes of reduced diameter and great length (figure 4a). This internal prestressing also protects the steel tendons against corrosion and is not so invasive. From the structural point of view, the most important advantage of modern prestressing is that improve the seismic performance of masonry structures in terms of stability, strength and ductility (energy dissipation). Another great advantage is the reversibility that allows the substitution for a better retrofitting measure. Figure 4a also shows the

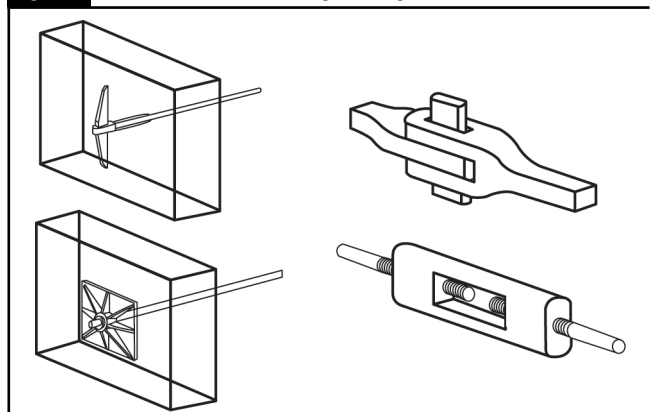
way that vertical prestressing may re-direct the horizontal forces induced by vaults and arches by the movement of their supports to a vertical resultant force transmitted to more stable elements. This horizontal movement may cause the out-of-plane failure (overturning) of supporting walls, or the collapse of the vaulted cover or arch. The external prestressing of figure 4b is less invasive than the internal one because it does not need to drill the masonry to insert the tendons, but in contrast, it is apparent and damages the architectonic value of the structure.

Figure 2. Old prestressing in Italian historical monuments.



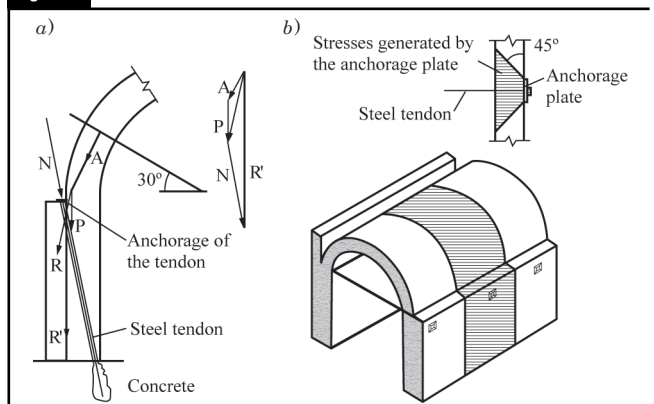
Note: a) the Roman Coliseum and b) vaulted structure in Pisa.

Figure 3. Metal bars with their anchorages and tighteners.



Source: Meli, 1998.

Figure 4. Post-tensioned steel tendons in vaulted structures.



Note: a) internal application (vertically) and b) external application (horizontally). Source: Meli, 1998.

4. 1. Prestressing devices

This section describes the general characteristics and behavior of several prestressing devices of different materials, including traditional prestressing steel and smart materials such as fiber reinforced polymers (FRPS) and nickel titanium (NITI) shape memory alloys (SMAS). In the context of this paper a prestressing device is a structural member axially stressed in tension and is integrated in general terms by two main parts, the anchorages and tendon. Normally, the anchorage material for prestressed concrete and masonry structures is high-resistance steel and more recently of innovative materials such as FRPS of different fibers (e.g. aramid, carbon and glass). On the other hand, the tendons could be commonly fabricated of prestressing steel, FRPS, SMAS and combinations.

4. 1. 1. Prestressing steel

Compared to conventional steel for reinforced concrete, prestressing steel was developed for prestressed concrete

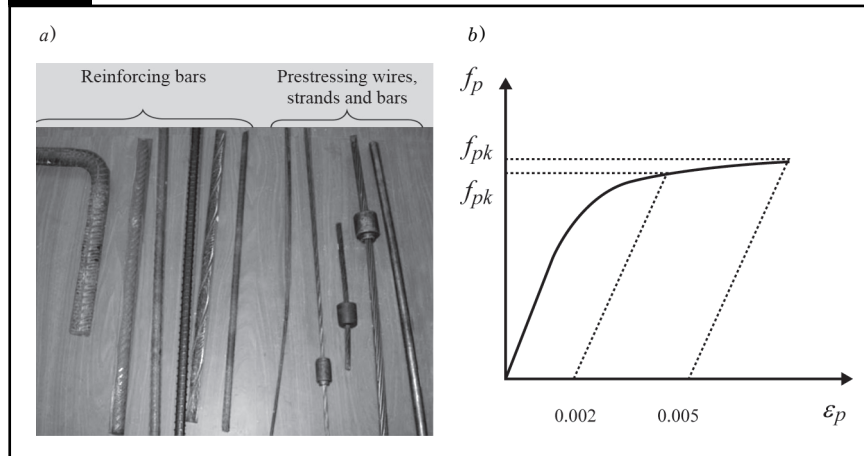
Table 1. Main forms of prestressing steel and their mechanical properties.

Type of prestressing steel	Tensile strength (MPa)	E modulus (MPa)
Cold drawn wire (5-7 mm)	1670 - 1860	210000
Cold drawn 7-wire strand (13-16 mm)	1770 - 1860	195000
Hot rolled bar (15-40 mm)	1030 - 1230	200000

Table 2. Main types of prestressing FRP bars and their mechanical properties.

Type of prestressing FRP	Tensile strength (MPa)	Strain at failure (%)	E modulus (MPa)
Arapree (7.5 mm)	1370 - 1506	2.40	62500
Technora (8 mm)	1900 - 2140	3.70	54000
CFCC (12.5 mm)	1870 - 2120	1.57	137300
Leadline (7.9 mm)	2250 - 2600	1.30	150000

Figure 5. Prestressing steel.



Note: a) comparison with reinforced concrete steel and b) characteristic stress-strain curve. Source: Sengupta and Menon, 2009.

structures due to its better performance. Nowadays, there is a great variety of prestressing steel, such as wires, strands, tendons (a group of strands or wires), bars and cables (a group of tendons) for bridges (figure 5a). The main properties of prestressing steel are the high tensile strength, stiffness, bond, flexibility, low corrosion and stress relaxation. As mentioned, relaxation has a great impact in the changes of prestressing forces with time. The main factors influencing this are creep (increase in deformation with sustained load) and shrinkage of concrete (contraction by loss of water and hydration heating of cement). The stress-strain behavior of prestressing steel when subjected to uniaxial tension becomes nonlinear and inelastic at a strain of 0.2% (yield point) for a stress beyond of approximately 70% or 80% of the ultimate stress (see figure 5b). There are three main forms of prestressing steel commonly used in post-tensioned structures: cold drawn wires, cold drawn 7-wire strands and the hot rolled bars (Ganz, 2001, DTES, 2005 and Sengupta and Menon, 2009). The main mechanical properties of the three types of prestressing steel are described in table 1.

4. 1. 2. Fiber reinforced polymers

With the continuous technological progress in the chemical industry in past decades, several FRPS composites have been introduced to the market for their use in prestressed concrete and more recently for the seismic retrofitting of historical masonry structures. Fibers of aramid (AFRP), carbon (CFRP) and glass (GFRP) have been used to manufacture bars, tendons (a group of bars), meshes and plates with different shapes, sizes, colors and resistances. Zhang *et al.* (2001) indicate that tendons made of AFRP (Arapree and Technora) and CFRP (CFCC and Leadline) bars are the most commonly used for prestressed concrete (figure 6). GFRP is considered less appropriate due to its low Young's modulus and is most commonly used as cables in mining engineering. The mechanical properties of AFRP and CFRP bars are described in table 2 taking into account reported data (Nanni *et al.*, 1996, Zhang *et al.*, 2001 and Dolan *et al.*, 2001). Compared to prestressing steel, FRPS are more resistant to corrosion, larger tensile strength, insensitivity to electromagnetic fields, 15-20% lighter and it is possible to incorporate optical fiber sensors for monitoring purposes.

The disadvantages of FRPS are their vulnerability to fire and brittle failure with no yielding, showing a stress-strain behavior linear at all stress levels up to the point of failure. The recommended prestressing force is of about 40% of the ultimate load capacity for AFRP and 60% for CFRP due to the stress-rupture limitations.

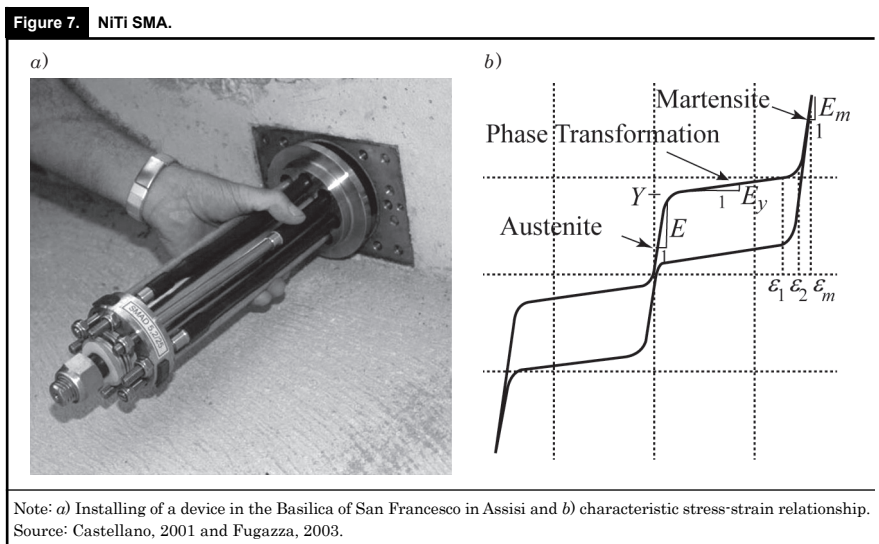
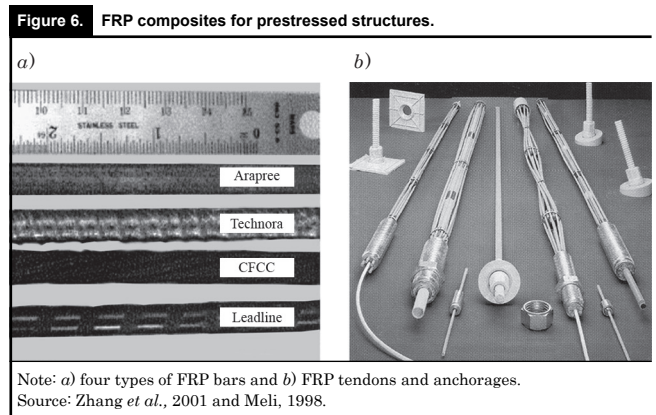
4. 1. 3. Nickel titanium shape memory alloys

Buehler and Wiley (1965) developed at the U.S. Naval Ordnance Laboratory (NOL) a series of tests on specimens of NITI alloys. An unusual behavior different from traditional materials was observed (Castellano, 2001, Fugazza, 2002, Preciado, 2011 and Ingalkar, 2014). The specimens were subjected to thermal cycles and presented nonlinear deformations (also named strain) of more than 8%, returning to the original position with no final permanent deformation (plastic strain). This effect was named shape memory and the material shape memory alloy (SMA). The material was subjected to further research and it was found that SMA also presented the property of superelasticity (or pseudoelasticity) when subjected to high temperatures (see figure 7). NITI SMA was later also named Nitinol SMA in honor to the laboratory where it was discovered. The fascinating behavior of this innovative material gained in a fast way the interest of the scientific community, being highly attractive for applications such as biomedical devices, energy dissipation and vibration control devices for the seismic protection of structures, aerospace structures, etc.

Recently, SMA material has been subjected to continuous research for the seismic retrofitting of ancient structures. figure 7a shows the first worldwide application of a NITI SMA device for the seismic protection of the facade of the Basilica of San Francesco in Assisi. SMA has the ability to undergo reversible micromechanical phase transition processes by changing their crystallographic structure. This capacity results in two major features at the macroscopic level which are the superelasticity and the shape memory effect (Fugazza, 2003). The SMA behavior is characterized by two main transformation phases: the austenite (A) and the martensite (S). These phases could be either thermal or stress induced. The phase transformation from A to S (forward transformation) starts when the SMA specimen is subjected to a uniaxial tensile stress larger than the A initial stress σ_f^{A-S} . At A finish

stress σ_f^{A-S} , the phase transformation is complete (martensite). When the specimen is subjected to larger stresses ($\sigma > \sigma_f^{A-S}$), the material exhibits the elastic behavior of the S phase. If unloading, the reverse transformation starts at a stress σ_s^{S-A} and is completed at a stress σ_f^{S-A} . The large deformations between both phases lead to the formation of a hysteretic loop in the loading/unloading stress-strain diagram (figure 7b).

Auricchio (1995), Auricchio and Sacco (1997), Desroches and Smith (2003) and Fugazza (2003) describe that the most common SMA devices used for engineering purposes are made of NITI wires, due to its relatively low cost and superior behavior compared to other SMA compositions. The main mechanical properties of different NITI SMA are presented in table 3. SMA possesses a unique combination of novel properties such as shape memory affect, superelasticity, high energy dissipation, damping capacity, fatigue and corrosion resistance. All these properties have converted SMA in a highly attractive material for engineering applications, especially for the



seismic protection of structures. Desroches and Smith (2003) affirm that SMA presents a brittle connection when welded to another material and dependency on the ambient temperature (as steel and other alloys) due to its thermoelastic nature (increase in temperature = decrease in stress). By changing the annealing temperature (heat treatment that alters the microstructure of a material), the transformation stress and the dissipated energy of NITI SMAS can be obviously changed, as this changes the transformation temperatures (Nemat-Nasser and Guo, 2006). The maximum plateau strain (the forward stress-induced transformation) increases with temperature, being 9% for specimens annealed at 873 K (Kelvin) (Huang and Liu, 2001). Moreover, its cyclic behavior presents low energy dissipation in the *A* form if compared to the *S* phase and forward transformation. In other words, if the SMA

is in the *A* phase behaves as a conventional material with reduced deformation (elastic strain). The superelasticity behavior (large deformation) and high energy dissipation is observed at the envelope (loop) formed by the *S* phase and forward transformation.

5. Applications of prestressing on historical masonry towers

Past intervention techniques used in ancient masonry towers have been used more as local strengthening of certain vulnerable structural parts than for a real improvement of the global behavior of the structure against EQS. This is a consequence of the limitations of existing materials in that time added to the lack of technology and knowledge about the real behavior of these structural elements (figures 8 and 9). A couple of metal bars of rectangular section were usually applied in horizontal way and in two directions in the internal part of towers, at belfry, in order to generate a better connection between walls to provide more stability. Moreover, this system was installed to avoid the out-of-plane collapse of the upper walls in EQ conditions (figures 8a and 9). On the other hand, the tower of figure 8b presents an application of metal bars at the perimeter of the upper part of the tower as belts aimed at fastening, to avoid with this the overturning. figure 9 depicts the old prestressing system described in section 4, including connections between segments, tightener and the anchorage inserted through the wall.

5. 1. The leaning tower of Pisa, Italy

One famous case of the application of post-tensioned steel tendons corresponds to the historical masonry tower of Pisa, Italy. The tower has a total height of 58.36 m with an external diameter of 15.54 m and an internal one of approximated 7.37 m. For this important monument, the seismic protection is not considered as the main problem. This worldwide famous tower has been presenting since its construction geotechnical issues (soil settlements) that started to generate its inclination, which induced critical concentration of stresses at certain parts of the structure. Sanpaolesi (1993) and Pavese (1997) describe that the safety of the tower was evaluated as a first stage, followed by the analysis of the most suitable retrofitting technique. A band of 18 post-tensioned steel tendons with a diameter of 15 mm each was horizontally installed at the identified critical section to confine the tower at this zone and to increase its overall strength. Fischli (1994)

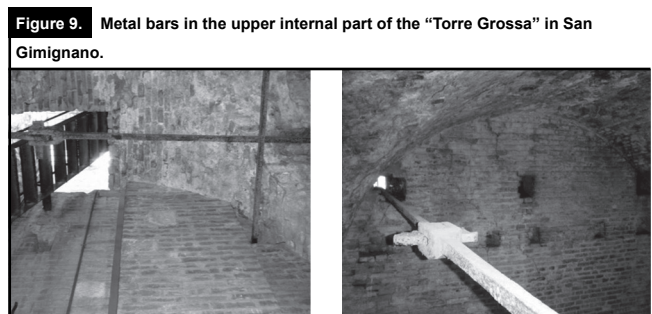
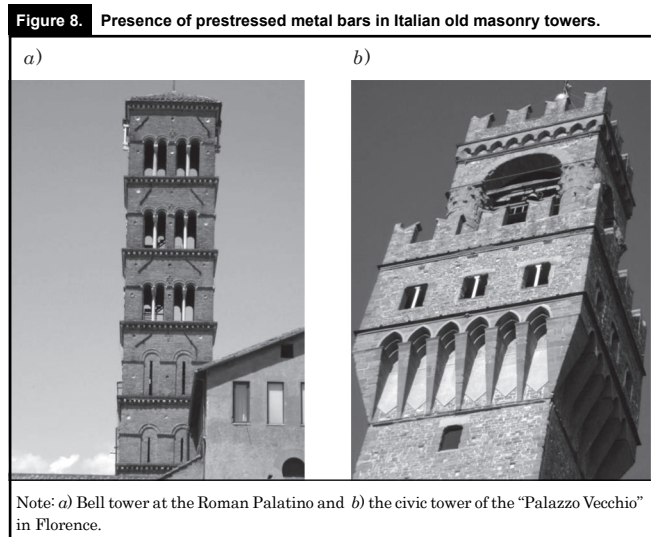


Table 3. Main mechanical properties of the commercial NITI SMA wires.

Type of SMA wire	E (MPa)	ϵ_L (%)	σ_s^{AS} (MPa)	σ_f^{AS} (MPa)	σ_s^{SA} (MPa)	σ_f^{SA} (MPa)
GAC® (0.64 × 0.46 mm)	47000	3	350	350	125	125
NDC® (1.49 mm)	60000	8	520	600	240	200
FIP® (2.01 mm)	80000	7	590	670	250	200

affirms that a counterweight of 600 ton was also installed on the north side of the foundation, aimed to stop its inclination and to induce to the tower to reverse. Even when these intervention works were considered as satisfactory in that time for the preservation of the monument, nowadays exists big concerning and controversy between the research community about the safety of the tower (figure 10) and the use of different retrofitting measures, because its vulnerability to suffer a sudden collapse is still imminent (Caldelli and Meucci, 2007).

5. 2. The general post office clock tower in Sydney, Australia

Another important case of the application of prestressing steel tendons corresponds to the historical clock tower of the general post office in Sydney, Australia (figure 11). Ganz (1990 and 2002) describes that the retrofitting intervention in this clock tower was finished in 1990 with the aiming of increasing its global seismic performance by means of vertical and horizontal prestressing as depicted in figure 11b. Four vertical post-tensioned steel tendons (19 strands of 12.7 mm diameter each and ultimate tensile strength of 3500 kN) were installed in drilled holes of 100 mm diameter through the corners of the tower. The four tendons were anchored and post-tensioned with prestressing forces of 1771 kN. Twelve horizontal prestressing bars of 35 mm diameter each and ultimate tensile strength of 1175 kN were installed at floor levels. The vertical and horizontal tendons were installed unbounded in order to allow the monitoring and future adjustment of the prestressing forces to compensate volumetric changes.

5. 3. The bell tower of the church of San Giorgio in Trignano, Italy

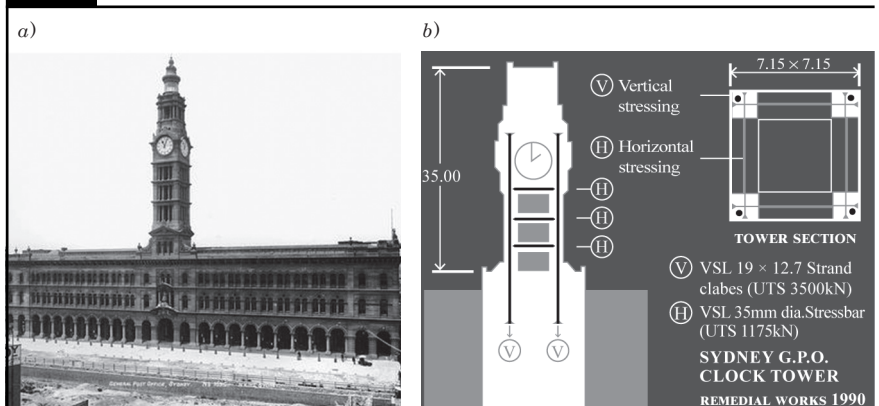
This historical masonry tower is located in Trignano, municipality of San Martino in Rio, Reggio Emilia, Italy (figure 12a). The tower has a total height of 18.5 m with a square base of 3 × 3 m, an average wall thickness of 0.36 m and it is surrounded on three edges by an adjacent building up to the height of 11 m. It was strongly damaged by an EQ occurred on October 15th, 1996 (magnitude 4.8, intensity VII). In 1999 the structure was rehabilitated by means of a replacement of the

damaged bricks and sealed up of cracks with especial mortars, as well as the application of new plaster on the internal and external walls. For the retrofitting intervention, all the floors were restructured using lighter materials such as timber and the bells were substituted. Moreover, a combination of devices such as steel tendons and SMA were vertically installed and without drilling at the four internal corners of the tower to increase its bending and shear resistance. Each of the four devices was integrated by six segments of steel tendons (to facilitate their assemblage) combined with one SMA located at the third floor (figures 12b-c). Every SMA was fabricated with 60 NITI superelastic wires (1 mm diameter and 300 mm length). The combined devices were anchored at the top and foundation of the tower and post-tensioned with a prestressing force of 20 kN (80 kN total force) in order to apply a distribution of compressive stresses to the masonry and to keep the applied force constant. This retrofitting intervention has been considered as the first world wide application of this innovative smart material on a historical masonry tower. The retrofitting was verified when a similar EQ in June 2000 (M4.5, intensity VI-VII) did not damage the tower, as explained by Indirli *et al.* (2001), Castellano (2001), Desroches and Smith (2003) and Fugazza (2003).

Figure 10. General view and neighbor buildings of the leaning tower of Pisa, Italy.



Figure 11. The general post office clock tower in Sydney, Australia.



Note: a) General view and b) details of the retrofitting measure. Source: Ganz, 1990.

6. Future perspective on the use of prestressing

In recent years, the suitability and energy dissipation enhancement of different prestressing devices for the earthquake retrofitting of old masonry constructions have been extensively studied for many researchers around the world (e.g. Sperbeck, 2009, Preciado, 2011, Foraboschi, 2013, Foraboschi and Vanin, 2013 and Fedele *et al.*, 2014). These investigations have been focused on the changes in prestressing forces, tendon material and combinations, optimal prestressing force, strength and ductility enhancement for energy dissipation of unreinforced masonry. Retrofitting by means of prestressing is designed horizontally or vertically in dependency on the aim of the strengthening. Horizontal prestressing has been mainly used in the cultural heritage to provide stability out-of-plane of walls or to reduce the tensile stresses generated by supports opening of vaults, arches and domes. On the other hand, vertical prestressing has proved to be more suitable to increase the in-plane lateral carrying capacity and ductility of masonry walls by providing tensile strength at key locations.

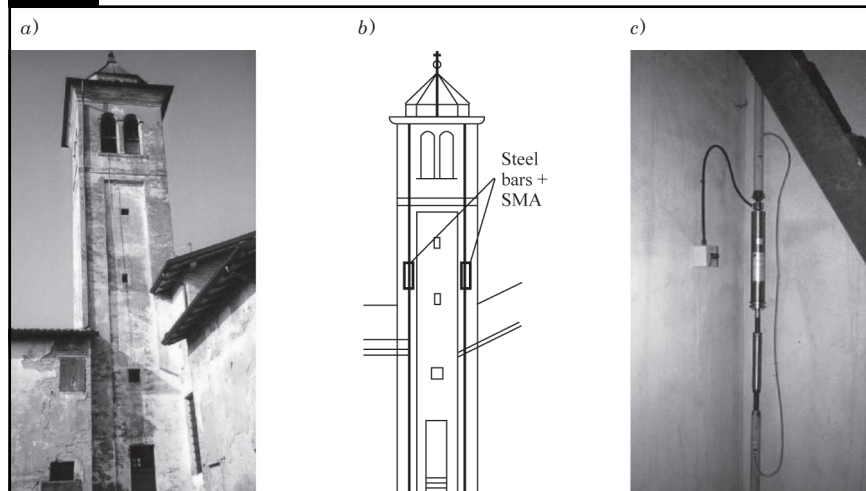
The level of improvement strongly depends on the level of prestressing force, so, the higher the initial prestressing force the higher the lateral strength enhancement. Especial careful may be taken into account in order to use this technique in historical masonry structures. This is due to the fact that prestressing may induce an exceeding of the intrinsic compressive strength of the structure, or to reduce the natural ductility of slender elements (e.g. bell-towers, light houses and minarets). Followed by a detailed diagnosis and seismic vulnerability assessment of the masonry building, an optimal prestressing level may be designed, due

to high prestressing levels could lead to local damage at the anchorage zone, or a complete sudden collapse even in static conditions by an exceedance of compressive stresses. Moreover, in seismic conditions, the compressed in-plane and out-of-plane toes (supports or bottom part of walls) could fail by crushing as well, and with this, to a brittle failure due to the explosive behavior of this mechanism. The proposal of an optimal prestressing force and device by means of parametric studies is strongly necessary. Based on extensive parametric studies, Preciado (2011) proposes an optimal prestressing force and FRP device that ensures an enhancement in strength and ductility with no failure by crushing in static and ultimate conditions during an EQ. The initial prestressing force is based on the self-weight of the structure and the device is compatible with the low elasticity modulus of old masonry and is completely removable for keeping the architectural value of the building.

By means of advanced drilling equipment is possible to insert prestressing devices into holes of small diameter and large height in order to be of minor invasion to the masonry by keeping the original architectonic appearance of materials and details (Foraboschi, 2013). This internal prestressing also protects the tendons against corrosion in the case of steel and from fire to FRPs. If the tendon is unbounded to the masonry, it is possible to calibrate the prestressing forces in the future due to relaxation of the material and temperature. Smart materials such as FRPs and SMAS have shown to be the most suitable for prestressing of historical masonry structures. These materials have similar properties (e.g. strength and elasticity modulus) than conventional materials, but enhanced performance (e.g. superelasticity), which may be highly exploited for seismic

energy dissipation purposes. Smart materials are also known as the materials of the future, being extensively investigated in terms of new alloys and fibers that behave different than conventional materials. Inside of FRPs tendons and meshes may be installed sensors for temperature and humidity measures and monitoring control of vibrations and prestressing forces. The monitoring control allows the set-up of early warning systems in case of EQs and actuators for prestressing devices that are activated only in case of an EQ. The prestressing system may be passive and activated by means of the actuator in EQ conditions. The suitability and

Figure 12. The bell tower of the church of San Giorgio in Trignano.



Note: a) General view, b) location of the retrofitting and c) installation of the devices.

Source: Indirli *et al.*, 2001.

effectiveness of early warning systems strongly depend on the EQ source, directivity and location from the source.

Summary

Unreinforced masonry is one of the main materials commonly found in ancient buildings, because this material goes back to the first civilizations that populated the earth. In the construction of old structures multiple typologies of masonry were used. During EQS, masonry structures are highly vulnerable to suffer strong damage due to the poor tensile strength of their materials. There is a great variety of modern techniques and advanced materials for the seismic retrofitting of masonry buildings. The selection of the appropriate technique and materials depends on the case study. The addition of different types of metal bars was a common practice in past prestressing interventions. Even with the enhancements on high resistance steel tendons used in modern prestressing, they are still vulnerable to corrosion and the excessive concentration of stresses induced to the masonry. The use of steel is not recommended as retrofitting of brittle old masonry structures due to the great difference in compatibility of deformations and susceptibility to corrosion. The recent tendencies on the seismic retrofitting of historical structures by prestressing are related to the use of smart materials of low elasticity modulus and high resistances such as tendons of FRPS and NITI SMAS. It was described in a general way three famous cases related to the application of prestressing in bell and civic towers. The application of these devices intends to improve the seismic behavior of the towers and to reduce the expected damage with the application of a pre-compression force

induced from the anchorage plate to the masonry. The compressive force generates a distribution of compressive stresses that compensates the tensile strength of masonry and structural stability at key locations identified in the seismic vulnerability evaluation. This enhancement has a great impact in the seismic energy dissipation, allowing to the masonry the capability of being more resistant and ductile, changing its failure mechanism from brittle to ductile. The structural stability is achieved by re-directing the horizontal forces induced by domes, vaults and arches by the movement of their supports to a vertical resultant force transmitted to more stable elements. This horizontal movement may cause the out-of-plane failure (overturning) of supporting walls, or the collapse of the vaulted cover or arch. A future perspective on the use of prestressed smart materials in historical masonry structures was also presented. The level of seismic improvement strongly depends on the level of prestressing force, so, the higher the initial prestressing force the higher the lateral strength and enhancement. Especial careful may be taken into account in order to use this technique in historical masonry structures because the compressive strength may be exceeded. The proposal of an optimal prestressing force and device is strongly necessary. Advanced drilling equipment allows the insertion of prestressing devices into holes of small diameter and large height in order to be of minor invasion to the cultural heritage. Smart materials have shown to be the most suitable for prestressing of historical masonry structures. Smart materials are also known as the materials of the future, inside of them may be installed sensors for monitoring control, early warning systems and actuators for application of prestressing forces.



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