ISSN (Online) 2394-2320

International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)

Vol 9, Issue 11, November 2022

Active Prestressing with Smart Materials for the Seismic Protection of Masonry Housing

[1] Adolfo Preciado*, [2] Alejandro Ramírez-Gaytán

[1] Departamento del Hábitat y Desarrollo Urbano (DHDU), Instituto Tecnológico y de Estudios Superiores de Occidente (ITESO), Periférico Manuel Gómez Morín 8585, 45604 Tlaquepaque, Jalisco, México.
[2] Departamento de Ciencias Computacionales, Centro Universitario de Ciencias Exactas e Ingeniería, Universidad de Guadalajara (UdeG), Boulevard Marcelino García Barragán 1421, 44430 Guadalajara, Jalisco, México.
Corresponding Author Email: [1] adolfopreciado@iteso.mx, [2] l7m8s3r@gmail.com

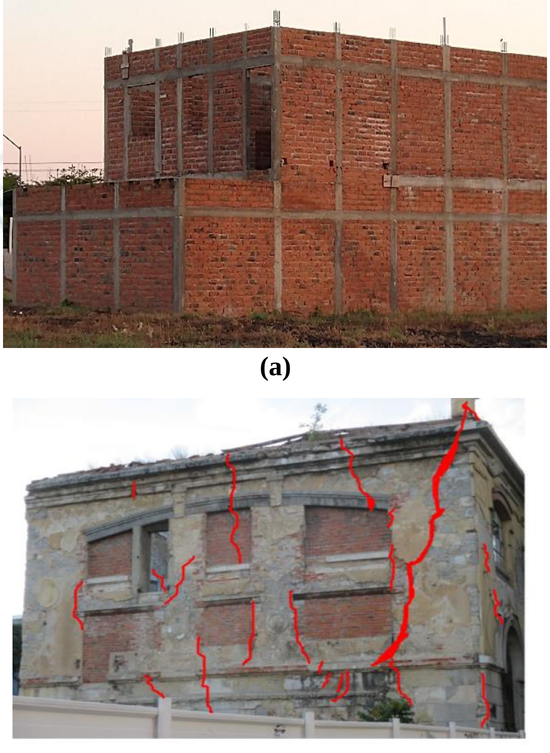
---

Abstract*— The addition of vertical and horizontal concrete ties in confined masonry has demonstrated to be an economic and suitable solution for obtaining structural integrity and prevents brittle failure. Conversely, the seismic energy dissipation of confined masonry is still doubtful in case of strong seismic action. The present research is objected at reviewing and describing several applications and smart materials (FRPs and SMAs) for the active prestressing on masonry structures. Moreover, to describe the seismic energy dissipative capability of active prestressing with smart materials in order to apply it in confined masonry housing, especially at the connection between masonry panel and vertical concrete ties. 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 add optical fiber sensors for monitoring. The SMA behavior exhibits two main transformation phases such as Austenite and Martensite that could be either thermal or stress induced and the superelastic performance is attractive for seismic energy dissipation. In further stages of this research, it is analyzed the feasibility of including economic horizontal prestressing devices of smart materials of SMA and FRPs in the joint between masonry panels and concrete ties.

Keywords: prestressing; smart materials; earthquakes; energy dissipation; masonry housing.

I. INTRODUCTION

Masonry is composed by the combination of units and mortar to form the different structural elements such as walls, columns, buttresses, arches, vaulted covers and domes. These structural elements are presented in the built environment, mainly housing and historical buildings (*e.g.* churches, bell-towers, castles and so on). In terms of strength, masonry is a material with a reasonable performance when subjected to compressive stresses under vertical transmission of loads, but conversely, very vulnerable against tensile/shear stresses under lateral seismic loads, ranging between 5-10% of the compressive resistance. In case of masonry housing located in high seismic zones of the world, the structural vulnerability of these structures is increased by the poor tensile strength of masonry and by other aspects relate to the lack of structural integrity, maintenance, irregularities in plan and elevation, local site effects and exposure to seismic sources (Fig. 1a).



(a)

(b)

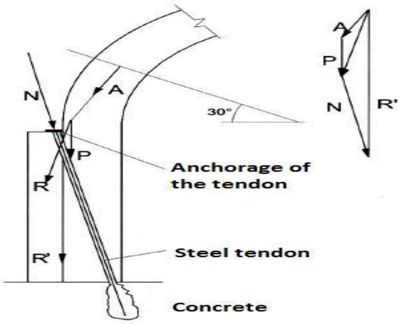
Figure 1. Unreinforced masonry in housing and historical buildings: (a) typical shear cracking propagation on unreinforced masonry buildings and (b) addition of confining concrete ties for structural integrity

Due to the aforementioned vulnerability aspects, the seismic performance of unreinforced masonry housing is inappropriate, leading to a reduce amount of dissipated seismic energy because of the lack of structural integrity and brittle collapses. To prevent brittle failure, unreinforced masonry housing is commonly designed with the addition of concrete ties in strategic vertical and horizontal locations inside the masonry panels (Fig. 1b) such as corners, intersections with other walls, to confine openings of doors and windows and to support concrete beams for transmitting the loads of slabs and use of the building. The present research is objected at reviewing and describing several applications and smart materials for the active prestressing on masonry structures. Moreover, to describe the seismic energy dissipative capability of active prestressing with smart materials in order to apply it in confined masonry housing, especially at the connection between masonry panels and vertical concrete ties.

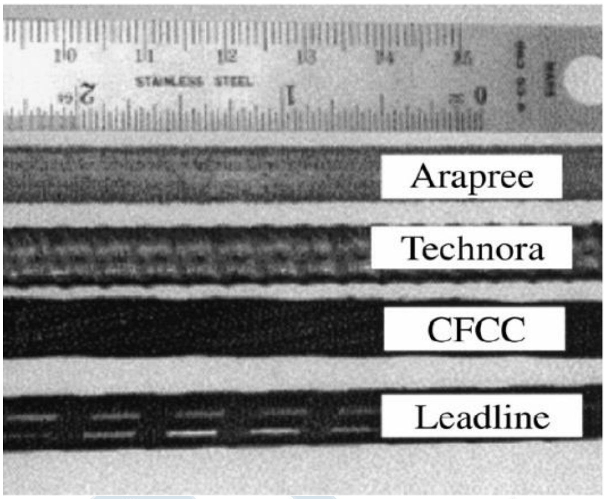
II. PRESTRESSING WITH SMART MATERIALS FOR SEISMIC ENERGY DISSIPATION

The technique of active prestressing has its beginnings several centuries ago, especially in Europe as observed in the unreinforced masonry building of Fig. 2a located in Pisa, Italy. The iron bars used to be heated until reaching a certain deformation by dilatation of the material, then an anchor was installed, or a segment of bar in the perpendicular direction to fix the prestressing. The precompression was transmitted to the masonry element by the induced contraction of the iron bar, and then, transmitted to the masonry as shown in Fig. 2b.

(a)



(b)



(c)

(d)

Figure 2. Active prestressing devices: (a) presence of old prestressing with iron bars (Preciado *et al.*, 2015); (b) correction of transmitted forces (Meli, 1998); (c) FRPs (Zhang *et al.*, 2001) and (d) SMA (Castellano, 2001)

The objective of the prestressing forces in this particular case (Figs. 2a-b) is to correct the transmission of diagonal loading of the vaulted cover to the masonry column. The diagonal loading is induced to the supports by lateral induced forces and opening of the vault by vibration, inducing vertical and horizontal loads when transforming the diagonal force into rectangular components. Then, the prestressing corrects the transmitted forces form the vault to the support by vertical forces, and due to the fact that masonry performs well under compression, the failure by overturning of the supporting columns is prevented. In past years, the use of iron bars was prevented due to its heavy weight, corrosion issues and complexity on heating the bars and installation. Instead, prestressing steel bars, wires and strands were commonly used, with superior tensile strength (1030-1860 MPa) and light weight if compared to iron bars (Table 1).

Table 1. Mechanical properties of prestressing steel

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

In past decades and with the technological progress in the chemical industry, several fiber reinforced polymers (FRPs) composites are being commercialized and with very interesting uses as prestressing devices. The most common fibers to reinforce the polymer matrix are made of Aramid (AFRP), Carbon (CFRP or CFCC), Technora (TFRP), Leadline (LFRP) and Glass (GFRP) (Fig. 2c). According to Zhang *et al.* (2001), the most common products for prestressing devices are bars, tendons (with more than two bars), meshes and plates with different shapes, sizes, colors and material properties. The most used FRPs for the seismic retrofitting of concrete structures by prestressing are CFRP and AFRP due to their material properties and similar/superior strength if compared to prestressing steel. Conversely, GFRP is more used for the seismic retrofitting of masonry structures due to its reduced elasticity modulus and strength (Table 2) leading to a better compatibility of deformations among materials (masonry and prestressing devices).

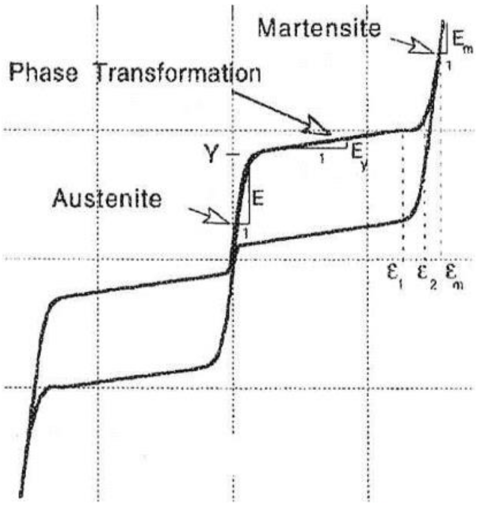
Table 2. Mechanical properties of prestressing FRPs

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

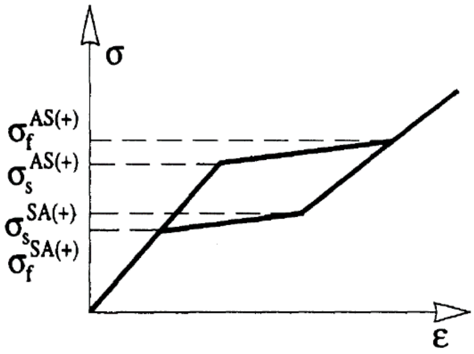
Table 3. Mechanical properties of commercial NiTi SMA wires

SMA wire	E MPa	ε_L %	σ_s^{AS} MPa	σ_f^{AS} MPa	σ_s^{SA} MPa	σ_f^{SA} MPa
GAC® (0.64x0.46 mm)	47000	3	350	350	125	125
FIP® (2.01 mm)	80000	7	590	670	250	200
NDC® (1.49 mm)	60000	8	520	600	240	200

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 main drawbacks of FRPs are their vulnerability to fire and brittle failure with no yielding, showing a stress-strain behavior linear at all stress levels until 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 limits. Buehler and Wiley (1965) developed at the U. S. Naval Ordnance Laboratory (NOL) several tests on specimens of nickel-titanium (NiTi) alloys and observed an unusual behavior different from traditional materials and named it as shape memory alloy (SMA). The behavior of this smart material gained the attention of the scientific community, being highly attractive for applications of energy dissipation and vibration control (Fig. 2d). The SMA behavior exhibits two main transformation phases (Fig. 3a): austenite (A) and martensite (S). These phases could be either thermal or stress induced (Preciado *et al.*, 2015).



(a)



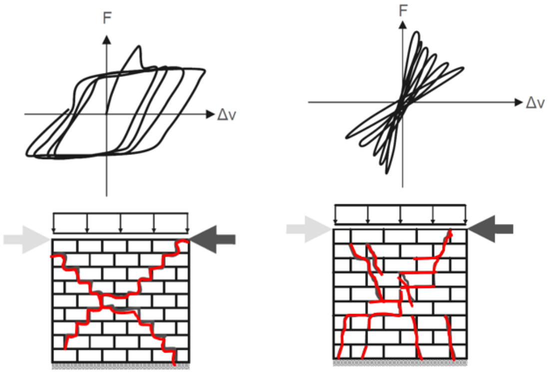
(b)

Figure 3. Superelastic performance of SMA: (a) Austenite and Martensite phase transformation (Fugazza, 2003) and (b) transmission of stresses among phases and superelastic performance (Auricchio, 1995, 1997).

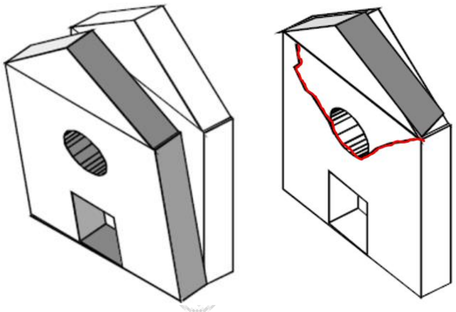
Moreover, (Fig. 3b) the phase transformation from A to S (forward transformation) starts when the SMA specimen is subjected to a uniaxial tensile stress larger than the A initial stress σs^{A-S}. At A finish stress σf^{A-S}, the phase transformation is complete (martensite). When the specimen is subjected 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 σs^{S-A} and is completed at a stress σf^{S-A} (Table 3). The large deformations between both phases led to the formation of a hysteretic loop in the loading/unloading stress-strain diagram (Preciado *et al.*, 2015). The main drawbacks of NiTi SMAs are the susceptibility to present brittle behavior when welded, the cost, ambient temperature dependency by its thermoelastic nature (temperature increase = stress decrease and vice versa). Several material models have been developed for the numerical simulation (Fig. 3b) of SMA wires in ANSYS® software by Auricchio (1995, 1997).

III. SEISMIC ENERGY DISSIPATION THROUGH CRACK PROPAGATION REDUCTION WITH VERTICAL PRESTRESSING

The typical seismic performance of masonry walls under in and out-of-plane seismic loads is presented in Fig. 4.



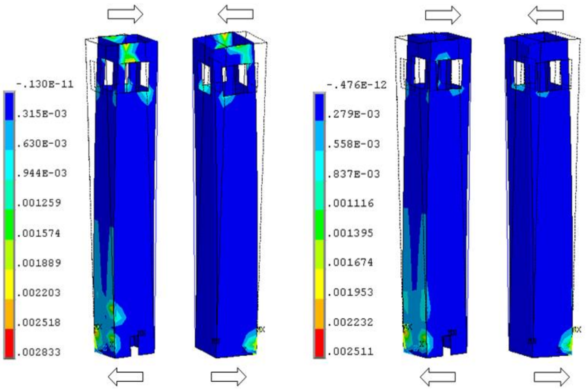
(a) (b)



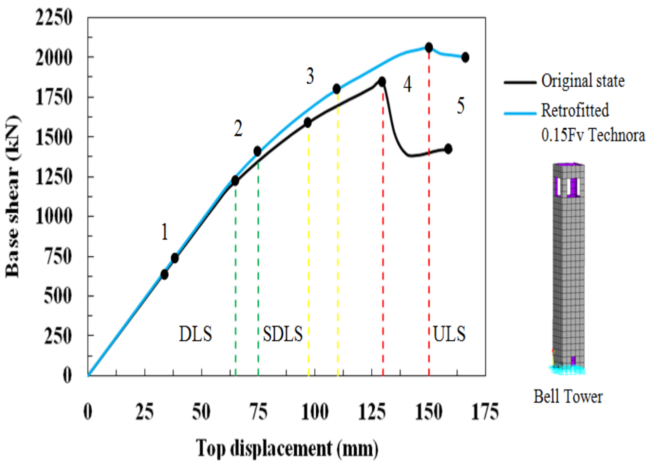
(c) (d)

Figure 4. In-plane and out-of-plane performance of unreinforced masonry structures: (a) stepped cracking; (b) diagonal cracking (Mistler, 2006); (c) façade collapse and (d) partial collapse (D'Ayala, 2000)

The performance of masonry walls depends on the direction of the seismic loading and vertical transmission of loads by the self-weight of masonry, use of the building and upper storeys. The in-plane stepped cracking (Fig 4a) is shown for low to intermediate levels of vertical loading or in case of mortar with reduced strength or absorption problems of the joint. This mechanism dissipates most of the seismic energy through the stepped cracking in the head and bed mortar joints as shown in the envelope of Fig. 4a. Conversely, the in-plane diagonal cracking goes through units and mortar due to the elevated vertical loads and the dissipative capability is lower than in the stepped cracking due to the high concentration of stresses and rupture of masonry (Fig. 4b). Moreover, the out-of-plane failure of masonry walls is brittle with no energy dissipation due to the lack of structural integrity and detachment of facades and gables from the rest of the building mainly due to the transmitted horizontal loads by the lateral walls or nave in churches (Figs. 4c-d). In order to verify the performance of different masonry walls and bell-towers (Fig. 5) with different openings and geometry, Preciado *et al.* (2016) used the material model of Gambarotta and Lagomarsino (1995) to simulate the seismic performance of masonry, as well as the SMA material model of Auricchio (1997) to simulate the contribution of active prestressing in the seismic energy dissipation under strong earthquakes.



(a) (b)



(c)

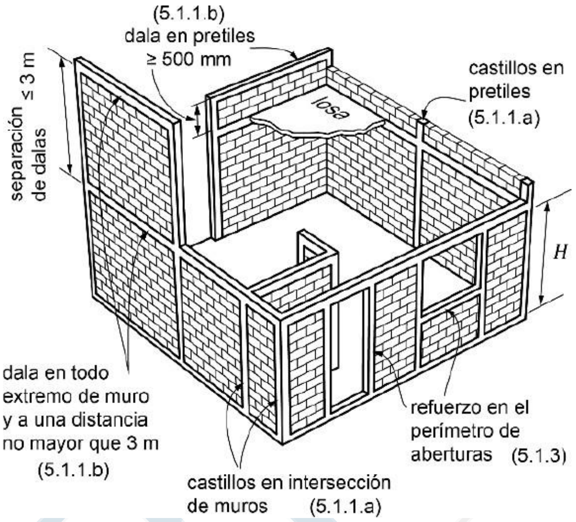
Figure 5. Bell tower. Comparison of principal plastic strain contours (front and back) at a displacement of 130 mm: (a) original state (ULS) and (b) retrofitted 0.15Fv Technora (Preciado *et al*., 2016)

The active prestressing devices where located vertically and with different variations of prestressing forces by considering as a pattern a percentage of the total vertical forces (weight of the structure) $\mathbf{F_v}$. Moreover, the SMA was used in small segments of 30 cm due to its cost and combined with FRP tendons of CFRP and AFRP, achieving good results on terms of failure mechanisms (Fig. 5a-b), performance and energy dissipation (Fig. 5c).

IV. FURTHER APPLICATIONS OF PRESTRESSING DEVICES IN MASONRY HOUSING

The further steps of this research are aimed at developing a GFRP or SMA prestressing device with low cost, and connect it to the joint between the masonry panels and the vertical concrete tie as observed in Fig. 6a.

(a)



(b)

Figure 6. Confined masonry with concrete ties: (a) Joint between masonry panel and vertical concrete tie (EERI, 2015) and (b) location of concrete ties and maximum spacing among confinements (NTC, 2017)

The prestressing devices will be tested by numerical simulations and horizontally located in the joint, the parameters under study are the location and geometry of the devices, combination of materials, tendons or plates, prestressing forces and anchorage, as well as seismic energy dissipation, failure mechanisms and so on. Moreover, in Fig. 6b is observed the specified location of concrete ties and spacing for confined masonry. In seismic zones is recommended not to exceed a spacing of 3 m among concrete ties (vertical and horizontal). The proposed retrofitting solution needs to be economic, easy to install in site, durable and reversible in case of detecting problems or localized cracking.

V. CONCLUSIONS

Unreinforced masonry structures are very vulnerable to suffer partial or total collapses in case of seismic action due to the intrinsic material properties of this material, geometry aspects and local site effects. The addition of vertical and horizontal concrete ties in confined masonry has demonstrated to be an economic and suitable solution for obtaining structural integrity and prevents brittle failure. Conversely, the seismic energy dissipation of confined masonry is still doubtful in case of strong seismic action. Therefore, it is proposed the addition of economic horizontal prestressing devices of smart materials of SMA and FRPs in the joints between masonry panels and vertical concrete ties. FRPs have interesting material properties with superior strengths and durability if compared to prestressing steel, being of great interest for the development of cost-effective devices of GFRPs due to its compatibility with masonry.

Furthermore, the SMA devices will be further investigated in order to use a different material or alloy with similar performance of the NiTi alloy and to take advantage of the superelastic behavior of this material for seismic energy dissipation.

REFERENCES

[1] Auricchio, F. (1995). “Shape memory alloys: Micromechanics, macromodeling and numerical simulations.” Doctoral thesis, University of California at Berkeley.
[2] Auricchio, F. and Sacco, E. (1997). “A one-dimensional model for superelastic shape-memory alloys with different elastic properties between martensite and austenite.” International Journal of Non-Linear Mechanics, 32: 1101-1114.
[3] Castellano, M. G. (2001). “Innovative technologies for earthquake protection of architectural heritage.” Proceedings of the International Millennium Congress: More than two thousand years in the history of Architecture, UNESCO-ICOMOS, Paris, France.
[4] D’Ayala, D. (2000). “Establishing correlation between vulnerability and damage survey for churches”. Proceedings of the 12th World Conference on Earthquake Engineering (12WCEE), 30 January - 4 February, 2000, Auckland, New Zealand.
[5] EERI (2015). “Construction guide for low-rise confined masonry buildings: A project of the World Housing Encyclopedia”. Earthquake Engineering Research Institute (EERI), USA.
[6] Fugazza, D. (2003). “Shape-memory alloy devices in earthquake engineering: Mechanical properties, constitutive modeling and numerical simulations”. Master thesis, University of Pavia, Italy.
[7] Gambarotta, L. and Lagomarsino, S. (1997) “Damage models for the seismic response of brick masonry shear walls”. Part I and II. Earthquake Engineering and Structural Mechanics, Vol. 26: 441-462.
[8] Meli, R. (1998). “Structural engineering of the historical buildings (in Spanish)”. Civil Engineers Association (ICA) Foundation, A. C., Mexico.
[9] Mistler, M. (2006). “Deformation-based seismic measure concept for masonry constructions (in German)”. Doctoral thesis, University of Aachen, Germany.
[10] NTC (2017). Normas Técnicas Complementarias para Ciudad de México “Normas Técnicas Complementarias para Diseño y Construcción de Estructuras de Mampostería.” México.
[11] Preciado, A., Bartoli, G. and Budelmann, H. (2015). “The Use of Prestressing Through Time as Seismic Retrofitting of Historical Masonry Constructions: Past, Present and Future Perspective”. Ciencia Ergo-Sum, 22(3): 242-252.
[12] Preciado, A., Sperbeck, S. T. and Ramirez-Gaytan, A. (2016). “Seismic vulnerability enhancement of medieval and masonry bell towers externally prestressed with unbonded smart tendons”. Engineering Structures, 122: 50–61.
[13] Zhang, B., Benmokrane, B., Chennouf, A., Mukhopadhyaya, P. and El-Safty, A. (2001). “Tensile behavior of FRP tendons for prestressed ground anchors.” Journal of Composites for Construction, 5 (2).