Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

SMAS FOR STRUCTURAL RESPONSE CONTROL, A SHORT REVIEW

Luigi Mollo[1], *Rosa Agliata*[2], *Carlo Giudicianni*[3]

ABSTRACT

There is an increasing drive toward the monitoring and control of the structural health by using smart materials. Smart materials have a long history in this application, and now the civil engineering industry is beginning to look to a substantial use of this technology to reduce damages originated by external environmental forces or by initial manufacturing and construction defects.

Many inspection techniques have been developed for detection, assessment and monitoring of damage and deterioration of structures, including various non-destructive evaluation techniques.

This paper gives an overview of research in the area of smart technologies based on the application of shape memory alloys for structural restoring and health monitoring, presenting a review of the basic properties and their applications in civil structures control.

Keywords: *Smart materials, Cultural heritage restoring, Shape memory alloys (SMA)*

1. INTRODUCTION

All in-service structures require some form of maintenance for monitoring and control their integrity and structural health, to prolong the lifespan of a structure and to prevent failure.

To this aim, the so called “smart materials” are very useful and interesting for civil engineering applications because they are able to respond to any external stimulus such that a change of temperature, pressure, electric or magnetic field by a change of their intrinsic properties (shape, conductivity, polarization, etc.).

The “smartness” refers to the exploitation of material properties to better serve a design function than would be possible through conventional techniques, designing and developing devices that can be integrated in an extremely non-invasive way.

Thanks to these advantageous characteristics, these devices are nowadays more and more employed in the rehabilitation of existing structures and generally for mitigation of building’s response to external actions (wind, earthquakes, thermal variation, etc.). In particular, they currently represent the best solution for retrofitting of suffering historical buildings that need interventions less invasive as possible.

According to their behavior, smart materials can be classified in two main categories.

To the first one belong materials that transform energy from one form to another one, in a directly and reversibly way: these are piezoelectric materials and electro/magnetostrictives materials.

The second class includes those that undergo changes in one or more of their properties – chemical, mechanical, electrical, magnetic or thermal – in direct response to a change in the external stimuli associated with the environment surrounding the material [1]. In this group are classified: electro/magneto-rheological fluids, optic fibers and shape memory alloys.

2. GENERALITIES OF SHAPE MEMORYALLOYS

This type of alloy has a marked ability to undergo huge deformations and to recover the previous shape after deformation without achieving any yield or plastic deformation.

---

[1] Civil Engineer,PhD, Academic researcher, Second University of Naples, Department of Civil Engineering, luigi.mollo@unina2.it
[2] Civil Engineer, Second University of Naples, Department of Civil Engineering,architettura.tecnica@unina2.it
[3] Civil Engineer, Second University of Naples, Department of Civil Engineering,architettura.tecnica@unina2.it

SMAs have the following behavior: an object in the low temperature martensitic condition, when plastically deformed under no external stresses, will regain its original shape when heated. This process is the result of a reverse martensitic transformation that takes place during heating. The martensitic transformation, which is the essence of the response of shape-memory alloys, may be illustrated simply by the change in martensite volume fraction with respect to temperature [2]. There are four important transition temperatures: martensite-finish (Mf), martensite-start (Ms), austenite-start (As), austenite-finish (Af).

There are many materials who exhibit the shape-memory effect (i.e. a lot of copper alloy systems), but the most common of the shape memory alloys is the Nickel-Titanium alloy, Nitinol (NiTi), because of its extraordinary shape-recovery performance: the material can be plastically deformed in its low-temperature martensite phase and then restored to its original configuration or shape by heating it above the characteristic transition temperature [2], that can be varied from –50 to 166°C. The plastic strains that can be completely recovered by heating Nitinol usually attains 6-8%. If during the heating, material's shape-recovery is blocked, Nitinol can endure stresses of 700 MPa.

Other special properties of SMSs are:

- The Young's modulus increasing within the phase transformation temperature range, during the heating process (in opposition to other materials, for which the Young's modulus decreases as the temperature increases).
- The damping characteristic that can be exploited for passive and adaptive dynamic control applications.
- The influence of the phase transformation on the electrical resistance: measuring the latter it's possible to determine the phase transition temperatures.

3. APPLICATIONS OF SMAs IN CIVIL STRUCTURES

SMAs have found applications in many areas due to their high power density, solid state actuation, high damping capacity, durability and fatigue resistance. The civil structures applications of SMAs can be passive (structural control), semi-active (active frequency tuning), or active (damage control) to reduce damage caused by environmental impacts.

3.1. SMAs for passive structural control

The passive structural control exploit SMAs damping property to reduce the response and the consequent plastic deformation of structures subjected to severe loadings, via two mechanisms: ground isolation system and energy dissipation system, which are different in arrangement and function.

A SMA isolator provides variable stiffness to the structure according to the excitation levels and in addition, energy dissipation and restoration after unloading.

A SMA energy dissipation element instead, principally mitigates the dynamic response of structures by dissipating energy.

3.1.1. SMA isolation devices

SMA made isolators, are installed between a super-structure and the foundation to filter the seismic energy transferred from the ground motion to the building: so that the damage is attenuated. Wilde et al. [3] investigated a base isolation system with super elastic SMA bars for elevated highway bridges, comparing SMA isolation system and a conventional isolation system. The results revealed that the damage energy of the bridge with the SMA isolation system is smaller than with the conventional one.

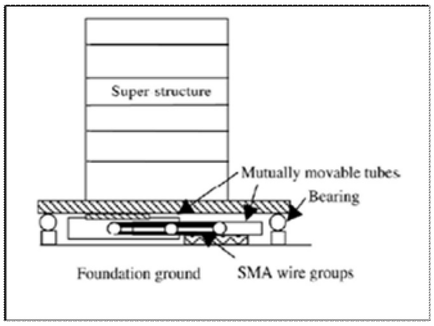

Fig. 1 Schematic of the SMA isolation system for buildings (from [4])

Dolce et al. [4] developed and tested the full-scale National-wire-based isolation system to study the possibility of using Nitinol wires for vibration isolation (Fig. 1). A superelastic SMA cable is wound around three stubs which are connected to the tubes, that through the reciprocal movement between the super-structure and the foundation, make wire elongation and so the vibration magnitude is damped by the wire.

Fig. 2 shows the experimental setup for the SMA spring isolation system developed by Mayes et al. [5] that demonstrate how the significant impact of SMA springs on the dynamic response of the vibration system is connected with two aspects: altering the system's resonance frequency and resonance amplitude.

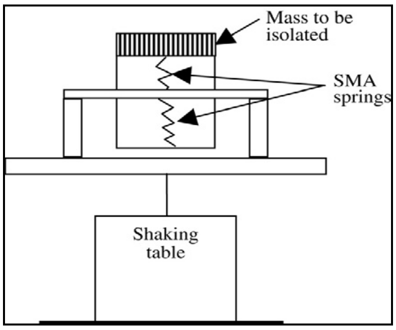

Fig. 2 Schematic of the SMA spring isolation device (from [6])

3.1.2. SMA Energy dissipation devices

Many experiments and simulations have been carried out to study the SMA-based energy dissipation devices in passive structure control. These devices are elements integrated into structures to absorb vibration energy through the hysteretic stress–strain relationship.

Generally SMA wire braces are installed diagonally in the frame structures, and they dissipate energy through stress-induced martensite transformation (in the superelastic SMA case) or martensite reorientation (in the martensite SMA case) after frame structures deformation under excitation.

These devices have characteristics of great versatility, simplicity of functioning mechanism, self-centering capability, high stiffness for small displacements and good energy dissipation capability. In fact experiments show that:

- vibration of the controlled frame with dampers decayed very much faster than that of the uncontrolled frame;
- the largest displacement of the controlled frame is only a low percentage of that of the uncontrolled one.

For example a shaking table test program was carried out by Cardone et al. [7] to evaluate the effectiveness of passive control SMA-based bracing systems for the seismic retrofitting of RC frames designed for gravity loads. The SMA brace was made of superelastic SMA wires fitted inside two concentric steel tubes tending to move relative to one another and producing double-flag-shaped hysteresis loops.

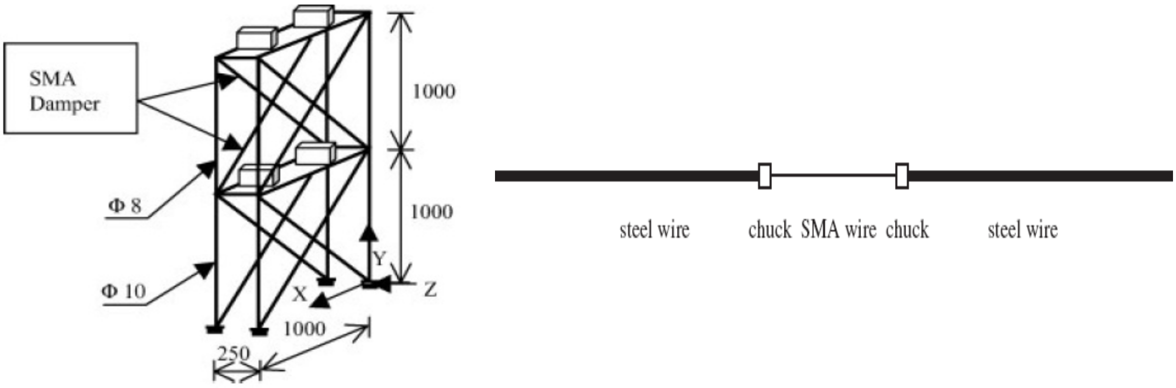

Fig. 3 Schematic of a two-storey frame and of a SMA damper (from [8])

Results confirmed the practical feasibility of using SMA-based braces in frame structures, which are characterized by lower weight and more recentring capability compared with steel braces.

Another interesting study case is the one of Yu-Han Lin et al. [8], who installed eight SMA dampers in a two levels steel frame structure to verify the effectiveness of this device. NiTi alloy wire is used to make the energy dissipation damper in this study, because this alloy has better energy dissipation property and higher resistance to corrosion and fatigue. The details of the SMA damper are shown in Fig. 3.

The functioning is based on the bigger tension stiffness of the steel wire than the SMA one, so when the frame is vibrating, the SMA wire will thus take almost all the deformation of the SMA damper and as a result, the SMA damper can dissipate vibration energy effectively.

Fig. 4 (left) shows that it takes about 45 seconds for the frame to decay its vibration from the initial displacement to half of it, while Fig. 4 (right) illustrates that it only takes less than 1s for the controlled frame to decay its vibration from the initial displacement to half of it.

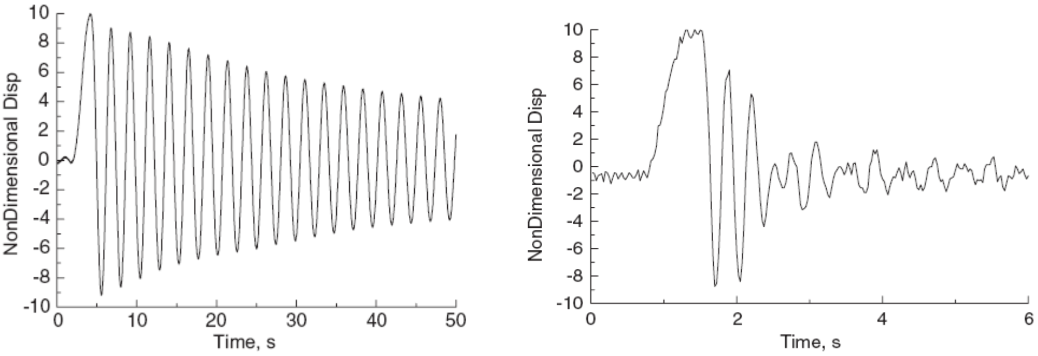

Fig. 4 Vibration decay history of the uncontrolled frame and of a SMA damper (from [8])

It's evident that vibration decay speed of the SMA dampers controlled frame is much faster than the uncontrolled frame one and so, considering the excellent property of energy dissipation and higher resistance to corrosion and fatigue, nickel–titanium SMA is quite suitable for making damper devices for vibration control.

3.2. SMAs for retrofitting of existing structures

3.2.1. Shape restoration and rehabilitation

Steel and fiber-reinforced polymer (FRP) are commonly used for retrofitting deficient structures but nowadays the SMAs are potential candidate for this applications, having some advantages over steel and FRP. An important property of superelastic SMA materials is its recentring capability. Moreover, SMAs are highly resistant to corrosion compared to steel and while FRP is brittle and vulnerable to fire, SMAs are ductile and have a higher resistance to fire, and its strength increases as the temperature increases up to a certain limit.

At University of Houston [9], was developed a way to use superelastic SMA wires to achieve a larger restoration force in the form of a stranded cable. Shown in Fig. 5 is a concrete beam (24 × 4 × 6 in.) reinforced with fourteen 1/8 inches diameter superelastic stranded cables via the method of post-tensioning to achieve a 2% pre-strain. After a load of 11,000 lbs and the appearance of a large crack (left), the crack on this beam was closed (right) under the elastic restoration force of the superelastic SMA cables upon removing the load.

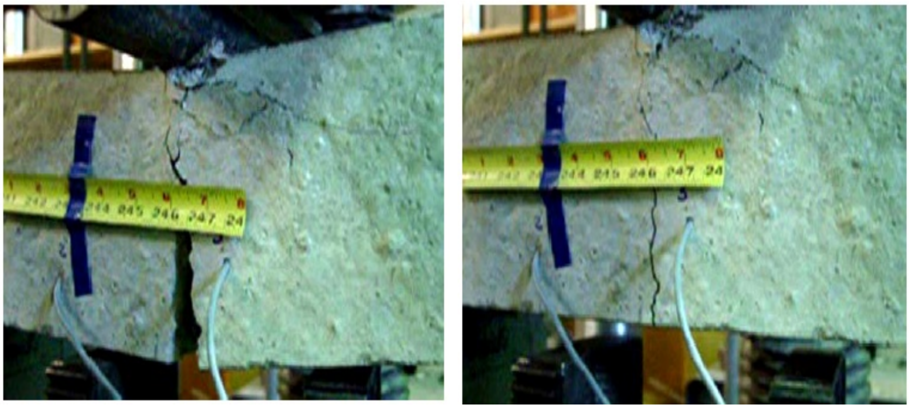

Fig. 5 A large crack during a loading test (left) and the crack closed after the loading test (right) [9]

Song and Mo [10] proposed the concept of Intelligent Reinforced Concrete (IRC) for structural self-rehabilitation by utilizing the actuation property of SMA, in particular through stranded martensite SMA wires post-tensioned. They monitored the electric resistance change of the shape memory alloy wires obtaining the strain distribution inside the concrete. In presence of cracks due to explosions or earthquakes, by electrically heating the SMA wires, the wire strands, contracts and reduces the cracks. The concrete structure is intelligent since it has the ability to sense and the ability to self-rehabilitate.

3.2.2. SMADs for earthquake-proof reinforcement of structures: two real Italian cases

In Italy, the presence of several ancient and historical interesting buildings and, at the same time, the high seismicity of the area, make the Cultural Heritage Structures (CUHESs) seismic protection one of the most important fields of the research and experimentation. The imperative necessity to rehabilitate most of these buildings is generated by their vulnerability also to moderate intensity seismic event, which can cause severe damages or collapse [11]. In order to avoid their ruin, nowadays, the research focalizes on new kind of restoring interventions, employing the so called "smart materials", in particular SMADs. These devices have been used for the first time in the rehabilitation of three ancient structures: the Bell Tower of the San Giorgio in Trignano Church (severely damaged by the 1996 Modena and Reggio Emilia earthquake), the Upper Basilica of San Francesco in Assisi and the Cathedral of San Feliciano in Foligno, both severely damaged by the 1997-98 Marche and Umbria earthquake [12].

The case of the Upper Basilica of San Francesco in Assisi [13]

One of most typical collapse mechanism in ancient churches is the tympana downfall, even though the remaining bottom portions of the façades remain standing. This behavior can be observed in the Upper Basilica of San Francesco in Assisi where the earthquake of September 26, 1997 destructed the vaults of the façade and transept and a portion of the left transept. Further, most of the vertical walls were in poor condition or damaged. It's important to underline that tympana walls, before the event, supported the reinforced-concrete beams of the roof structure so that, it was impossible to control the forces exchanged between the two elements during a seismic action.

Every crack was developed from the ground level up to the level of the threshold of the high windows. It was necessary a structural protection to prevent serious damage, excluding both the use of injections of reinforcement (because of the presence of frescos), and traditional connections by steel bars between the Basilica's roof and the tympanum (too stiff and dangerous for the tympanum itself).

Sothe exceptional characteristics of SMA devices seemed to be particularly advantageous in this case. A. Bonci et al. [13], in order to modify the roof-tympanum interaction, disconnected the roof from the tympanum wall and decided to build new truss of concrete to support the roof beams and to transfer vertical loads on the transept walls. Further of this the collapsed portion of the left tympanum was rebuilt, removing the transept tympana deformations.

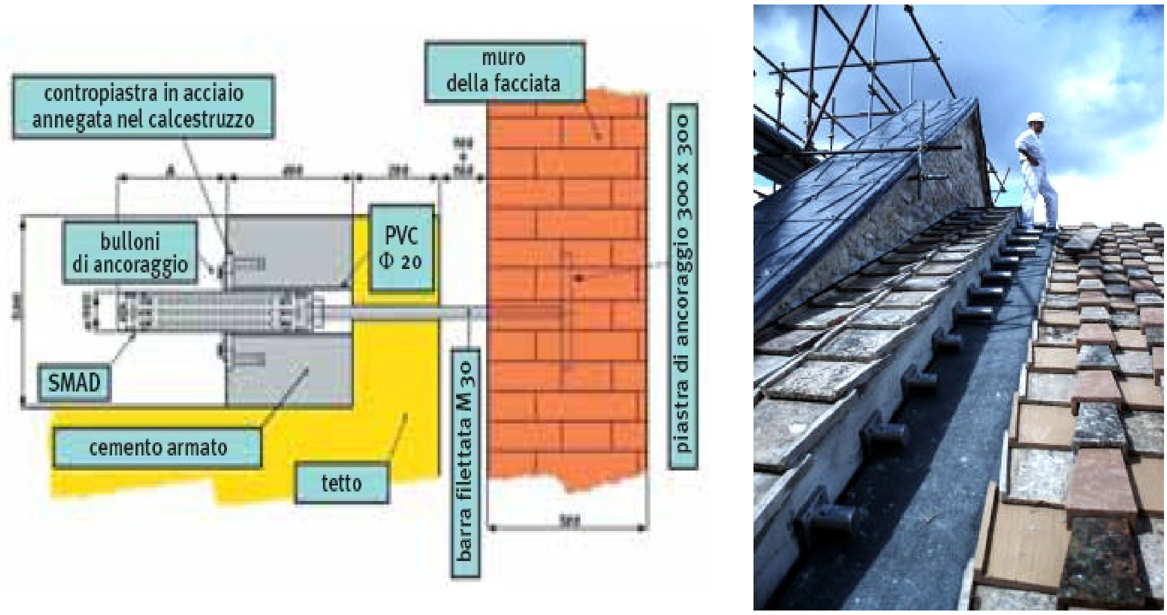

Fig. 6 SMAD device applied to the Basilica (left, from [14]) and the three sets of SMADs (right, from [13])

The new concrete truss has been connected to the tympanum wall by using SMADs to distribute the exchanged forces. In particular have been used "multi-plateau" devices, with different properties and lengths that determine a different force displacement behavior. Each device is composed of three sets of SMA wires, working in series for different values of the external action. For the connection of the two transept tympana were used 24 SMADs on the south side and 23 on the north side (Fig.6).

The case of San Giorgio Church Bell-Tower [11]

The San Giorgio in Trignano Bell-Tower (in San Martino in Rio) had been literally cut into two pieces, fortunately remaining superposed [11], by the earthquake of October 15th 1996: this type of failure is a typical collapse mechanism of high, thin structures (i.e. towers).

The most common intervention to prevent breakdown caused by seismic actions, is the insertion of TD vertical bars (tensioned to apply pre-stress to the masonry) which run through the height of the tower and are anchored at its foundation.

For San Giorgio Bell-Tower, the effectiveness of this intervention has been improved using SMADs in series with the steel bars (Fig. 7), that permit the control of the force imposed by the bars to the masonry walls; actually, with a SMAD proper design, the force transmitted to the tower shouldn't be higher than the "upper plateau" of the SMA elements used in the device.

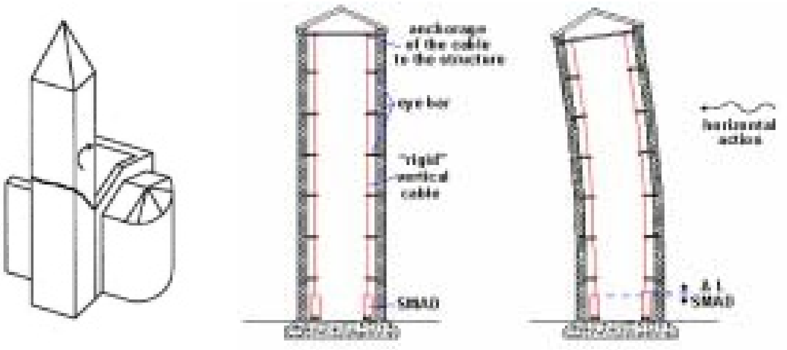

Fig. 7 Flexural collapse of a bell tower (left) and proposal of use of SMADs on slender buildings (right) [11]

This restoring intervention permitted a structural reinforcement and an increasing of modal frequencies, which made possible to this historical tower to stay intact after a similar earthquake in 2000, without suffering any damage, in opposition to other structures rehabilitated with traditional techniques.

4. CONCLUSIONS

This paper presents a short review of the basic properties of shape memory alloys (SMA) and their applications in passive control of civil structures. It was discussed in detail the application of devices consisting of SMA for the reinforcement and rehabilitation of existing structures, confirming the feasibility and the effectiveness of these strategies for mitigation of the structural response and in any case to restore the state of the buildings damaged by external actions (generally earthquakes) in a completely non-invasive way. Considering the excellent property of energy dissipation and higher resistance to corrosion and fatigue, SMA devices are suitable for making damper devices for vibration control.

In summary, it's possible to conclude that the potential of SMADs in structural applications has been clearly demonstrated through laboratory research and application to real cases.

REFERENCES

[1] Addington D. M., Schodek D. L. (2005) *Smart materials and new technologies for the architecture and design professions.* Architectural Press, an imprint of Elsevier, Oxford/ Burlington MA, (ISBN 0 7506 6225 5).

[2] Rogers C. A., Giurgiutiu V., Leung C. K. Y. (2000) Smart materials for civil engineering applications. In Lopez-Anido R. A. and Naik T. R. *Emerging materials for civil infrastructure.* ASCE, Reston (ISBN 0 7844 0538 7).

[3] Wilde K, Gardoni P., Fujino Y. (2000) Base isolation system with shape memory alloy device for elevated highway bridges. *Engineering structures* 22(3): 222-229.

[4] Dolce M., Cardone D., Marnetto R. (2001) SMA re-centering devices for seismic isolation of civil structures. In: *Proc. of SPIE* 4330, 238-49.

[5] Mayes J.J., Lagoudas D., Henderson B.K. (2001) An experimental investigation of shape memory alloy pseudoelastic springs for passive vibration isolation. In: *Proc. AIAA space,* Albuquerque.

[6] Khan M.M., Lagoudas D. (2002) Modeling of shape memory alloy pseudoelastic spring elements using Preisach model for passive vibration isolation. In: *Proc. of SPIE* 4693, 336-47.

[7] Cardone D., Dolce M., Ponzo F.C., Coelho E. (2004) Experimental behavior of R/C frames retrofitted with dissipating and re-centering. *Journal of Earthquake Engineering* 8(3): 361-393.

[8] Han Y.-L., Li Q. S., Li A.-Q., Leung A. Y. T., Lin P.-H. (2003) Structural vibration control by shape memory alloy damper. *Earthquake Engineering & Structural Dynamics* 32(3): 483-493.

[9] Song G., Ma N., Li H.-N. (2006) Applications of shape memory alloys in civil structures. *Engineering Structures* 28(9): 1266-1274.

[10] Song G., Mo Y.L. (2003) *Increasing concrete structural survivability using smart materials*. A proposal submitted to Grants to Enhance and Advance Research (GEAR), University of Houston.

[11] Indirli M., Forni M., Martelli A., Spadoni B., Venturi G. (2001) Further new projects in Italy for the development of innovative techniques for the seismic protection of cultural heritage. In: *Proc. of 7th International Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures* Assisi.

[12] Indirli M., Bertocchi A., Cami R., Procaccio A. (2002) Ongoing Research Projects at ENEA and Pilot Applications for the Seismic Protection of Cultural Heritage. In: *Proc. of the Third World Conference on Structural Control* Como, ed. Wiley.

[13] Bonci A., Carluccio G., Castellano M.G., Croci G., Infanti S., Viskovic A. (2001) Use of shock transmission units and shape memory alloy devices for the seismic protection of monuments: the case of the Upper Basilica of San Francesco at Assisi. In: *Proc. of International Millennium Congress, More than Two Thousand Years in the History of Architecture* UNESCO-ICOMOS, Paris.

[14] Indirli M. (2007) Interventi con moderne tecniche antisismiche su edifici storici in muratura. *Costruire in laterizio* 118(4): 52-53.