*Smart Structures and Systems, Vol. 4, No. 2 (2008) 233-245*
DOI: http://dx.doi.org/10.12989/sss.2008.4.2.233


# Aseismic protection of historical structures using modern retrofitting techniques

C. A. Syrmakezis*, A. K. Antonopoulos and O. A. Mavrouli

*Institute of Structural Analysis and Aseismic Research, National Technical University of Athens, 9, Iroon Polytechniou St., GR15773, Zografou Campus, Athens, Greece*

*(Received June 20, 2007, Accepted July 16, 2007)*

**Abstract.** For historical masonry structures existing in the Mediterranean area, structural strengthening is of primary importance due to the continuous earthquake threat that is posed on them. Proper retrofitting of historical structures involves a thorough understanding of their structural pathology, before proceeding with any intervention measures. In this paper, a methodology is presented for the evaluation of the actual state of historical masonry structures, which can provide a useful tool for the seismic response assessment before and after the retrofitting. The methodology is mainly focused on the failure and vulnerability analysis of masonry structures using the finite element method. Using this methodology the retrofitting of historical structures with innovative techniques is investigated. The innovative technique presented here involves the exploitation of Shape Memory Alloy prestressed bars. This type of intervention is proposed because it ensures increased reversibility and minimization of interventions, in comparison with conventional retrofitting methods. In this paper, a case study is investigated for the demonstration of the proposed methodologies and techniques, which comprises a masonry Byzantine church and a masonry Cistern. Prestressed SMA alloy bars are placed into the load-bearing system of the structure. The seismic response of the non-retrofitted and the retrofitted finite element models are compared in terms of seismic energy dissipation and displacements diminution.

**Keywords:** masonry; seismic respons; finite element analysis; failure; vulnerability; seismic retrofitting; SMA.

## 1. Introduction

The seismic rehabilitation and retrofitting of historical structures is an important issue in the entire Mediterranean basin, which is characterized by its richness in historical masonry structures. The high seismic risk in the area poses a continuous threat to such type of structures and their protection becomes imperative whether their operation remains the same or when new operation requirements are considered. The exceptional character of historical structures, owed to their cultural, social and architectural value imposes the respect of their originality, thus any protection measures should comply with the principles of reversibility and compatibility. For this purpose thorough understanding of the structural pathology and of the structure's possible seismic response is necessitated.

Masonry structures and especially historical ones present some peculiarities. For this purpose, the analytical methodologies for the evaluation of their seismic response should be differentiated from those followed for modern reinforced concrete or steel structures. The afore-mentioned peculiarities are

*Corresponding Author, E-mail: isaarsyr@central.ntua.gr

mainly associated with the massive distribution of their weight, resulting in the application of seismic inertia forces all over the structure, as well as with simulation uncertainties that are introduced during analysis. These uncertainties mainly concern geometry, mechanical properties, past damage, degradation of materials etc. The influence of these factors should be taken into consideration for the realistic evaluation of the response historical masonries to earthquake loads.

The finite element method is widely used for the analysis of masonry structures and the calculation of stresses, displacements and dynamic structural properties. The further elaboration of the finite element analysis results demands the use of specialized software and methodologies. For this purpose, the methodologies that are presented in this paper exploit the first stage finite element analysis information in order to locate problematic areas on the structure, to identify possible causes of failure and to specify, on a quality and quantity basis, their seismic vulnerability. Consequently, minimization and optimization of interventions as well as calculation of the residual risk after the application of protection measures can be obtained.

When it comes to the conservation or restoration of historical structures, traditional retrofitting techniques, often, are proved ineffective, due to their irreversible and incompatible character. The application of damper systems, instead, for the dissipation of seismic energy has a very satisfactory performance, offering reversibility, minimization of intrusiveness and durability. Shape Memory Alloys (SMA) are smart materials that are characterized by Young's modulus-temperature relations, the shape memory effect, the superelastic effect and high damping properties (DesRoches and Smith 2005). These characteristics can be used for the development of innovative structural rehabilitation and retrofitting techniques, based on SMA dampers.

In this framework, the efficiency of SMA for the seismic protection of historical masonry structures and monuments is investigated. The investigation is made through the analysis of an outstanding monument situated in Greece, the Church of Agios Panteleimonas and the Cistern, belonging to the monastery complex of Nea Moni of Chios. The aforementioned specialized methodologies are applied on the finite element analysis model, before and after the use of SMA bars and comparative results are obtained concerning the efficiency of the retrofitting method.

## 2. Evaluation of the seismic response of historical structures

### *2.1. Evaluation of the actual state of the structure*

The investigation and documentation of the actual state of a structure is important for the retrofitting decision taking. For the evaluation of the actual structural state of a historical structure, the deep comprehension of its structural pathology is imperative. Especially in the case of historical structures, general deterioration and local damage are caused by several coexisting actions rather than a unique one. For the investigation of these synergistic actions a multidisciplinary approach on the protection of historical structures and monuments is necessary.

Before proceeding with any intervention actions, main pathological causes of historical structures have to be classified, as follows:

a. internal causes, related to the structure

b. external causes, related to its environment

Main internal causes are:

a. material characteristics (quality, reliability, degradation, etc)
b. performance of the structural members (bad conception, incompatible materials, low construction quality, insufficient connections, etc.)

External causes are mainly related to:

a. accidental actions, usually of high intensity and rare: fire, foundation sliding, foundation settlement, earthquake, etc
b. environmental actions, usually of low intensity and permanent: mechanical effects (e.g. vibrations due to normal traffic), thermal effects (e.g. dilatation problems), humidity effects (e.g. wetting -drying cyclic action, water penetration, etc), physical -mechanical effects (e.g. erosion by rain), physical -chemical effects (e.g. physical -chemical attack for embedded elements), chemical attack (e.g. sulphate attack due to crystallization of salts), corrosion attack (e.g. on wooden elements, steel elements, etc), root action, etc.

The complexity of the evaluation problem is emphasized by the fact that the majority of historical structures have been subjected to many past actions: architectural interventions, devastations from fires, earthquakes, war attacks, non compatible restoration and consolidation attempts, all of which have resulted in the modification of the original structural concept.

### 2.2. Earthquake response assessment using the finite element method

For the analysis of masonry structures, their peculiarities have to be considered. The distribution of the structure's mass all over its volume and the relative insignificance of masses concentrated at the floor levels are characteristics that do not allow for assumptions applicable to modern structure. Lack of monolithic connections is a further masonry peculiarity. As a result, for the adequate modelling of masonries, proper modification of mathematical models already used for modern structures is required.

The finite element method is strongly recommended as it can provide a reliable distribution of masses along the structure and a realistic simulation of inertia forces imposed on it. Additionally, it offers the advantage of flexibility during simulation as far as geometry, boundary conditions, etc. are concerned.

The most commonly employed finite element type for this purpose is the shell element, activating six degrees of freedom on each joint. However, in some cases, the widely used discretization using 2D finite elements (shell, plate or membrane) can be proven insufficient. This may happen when finite elements' thickness representing the wall width is considerably greater than their plan dimensions. Inadequate model formulation using plane finite elements is also observed in the case of architectural particularities (i.e. walls presenting width variations) where assumptions required to effect dimensionality reduction in order to use two-dimensional elements for the analysis, may be proved misleading. In such cases, the use of 3D solid elements is strongly recommended.

Depending on the required information on the structural response, response-spectrum analysis or time history analysis can be performed, among others. Information concerning ground motion parameters is different in each case; in the former case the response spectrum should be introduced, while in the latter case an accelerogram is necessary. These data can be obtained from seismological data of the area of the historical monument. Otherwise, national and international codes and suggestions may apply for the design values.

Finite element analysis results may provide useful information concerning displacements of the structure, developed stresses, dynamic properties, structural damping capacity etc. However, given that the real structure obeys nature and not mathematical laws, analysis mainly aims at the provision of an indication of the structural performance instead of a unique solution to a given problem.

### 2.3. Seismic failure evaluation

An important indicator of historical structures seismic performance is the qualitative and quantitative calculation of structural failure. Failure analysis, following stress analysis, gives an indication of the masonry susceptibility to damage, under specific loading assumptions. For this purpose the modified Von Mises failure criterion is used (SAP 2000). The modified Von Mises failure surface is formed by the interaction of four surfaces S1, S2, S3, and S4, as shown in Fig. 1 for zero shear stress. The failure surface is defined by Eqs. (1)-(4).

S1: $$\sigma_{xx}^2 + \sigma_{yy}^2 - \sigma_{xx}\sigma_{yy} + 3\tau^2 - f_{wc}^2 = 0, \quad \text{for} \quad \sigma_{xx} \text{ and } \sigma_{yy} \le 0 \tag{1}$$

S2: $$\sigma_{yy} + (1-\sigma_{xx}/a)\sqrt{f_{wc}^2 - 3\tau^2} = 0 \quad , \quad \text{for} \quad \sigma_{xx} \ge 0 \text{ and } \sigma_{yy} \le 0 \tag{2}$$

S3: $$\sigma_{xx} + \sigma_{yy} - a = 0, \quad \text{for} \quad \sigma_{xx} \text{ and } \sigma_{yy} \ge 0 \tag{3}$$

S4: symmetrical to S2 in respect to the bisectional level of the first quadrant

where: $$a = (f_{wt}/f_{wc})\sqrt{f_{wc}^2 - 3\tau^2} \tag{4}$$

The "FAILURE" software (Syrmakezis and Asteris 2001) is used for the elaboration of principal stress data and the generation of graphical and statistical outputs, showing the type, extent and location of failure.

The seismic vulnerability evaluation of a structure is subsequent to its failure analysis, incorporating additionally the uncertainties that are introduced during its analytical simulation. It is associated with the structure's expected performance when subjected to a single seismic event, through the definition of a correlation function between this action and the probability of exceeding a certain response level, accounting, at the same time, for random values of a structure's property referred to as the observation parameter. The illustration of this function can take place through a fragility curves diagram, which associates the cumulative probability of exceeding a certain response level with the seismic intensity index.

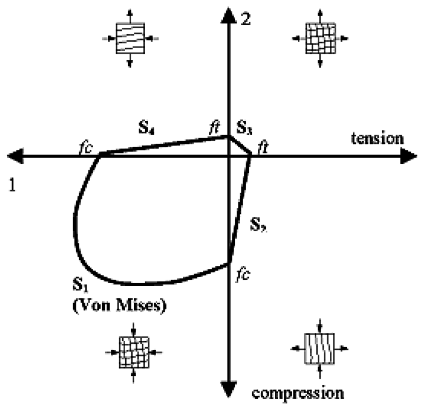



Fig. 1 The modified Von-mises failure criterion

The developed methodology is based on the statistical elaboration of structural failure results that have been obtained by parametric analyses (Syrmakezis, *et al.* 2005). For this purpose, various values of the seismic indexes as well as of the observation factor are considered. The most common probability distribution functions, selected to fit the data, are the normal and the lognormal. The probability density function of the normal distribution is defined by Eq. (5).

The variable $x$ follows a lognormal distribution, if the quantity $y = \ln(x)$ can be expressed by the normal distribution.

$$f(x) = \frac{1}{\sqrt{2\pi}\, s_x} \exp\left[-\frac{1}{2s_x^2}(x-m)^2\right], \qquad -\infty < x < \infty \tag{5}$$

where $s_x$: standard deviation
$m$: mean value

In the case of historical masonry structures, the observation factor is usually selected to be masonry's flexural or tensile strength, since it is closely related to its seismic performance and it usually presents large dispersal. The seismic intensity index, representing the seismic hazard, is usually selected to be the Peak Ground Acceleration (PGA). Alternatively, other ground motion parameters can be used to represent seismic intensity such as: Spectral Acceleration (SA), Peak Ground Velocity (PGV), Spectral Velocity (SV) and Spectrum Intensity (SI). The response index, which represents the seismic response of the structure, is defined according to the proposed methodology to be equal to the ratio of the wall area that has failed divided by the total wall area, as shown in Eq. (6). This type of index can provide an indication of the damage extent and of the repair cost for a wall surface.

$$DI = \frac{A_{fail}}{A_{tot}} \tag{6}$$

## 3. Retrofitting of historical structures using SMA

### *3.1. The retrofitting process*

The rehabilitation design process consists of three basic steps: the collection and evaluation of general data, the investigation of the actual state of the structure and athe selection of the retrofitting intervention to be applied after investigating alternative solutions.

Collection and evaluation of general data involves:
a. historical data: history of the structure, old photos, other written documents, etc.
b. geological data: area geological data, hydrogeological data, etc.
c. climatic data: rain, temperature, humidity, etc.
d. seismological data: historical seismological data (information), recent seismological data (instruments), etc.
e. aseismic design data: geological and seismotectonic maps, earthquake accelerograms (design values), aseismic codes provisions, etc.

Investigation of the actual state of the structure comprises:
a. collection of architectural data: drawings of existing structure, photographic documentation, technical

report, etc.

b. investigation of the structure and collection of structural data: drawings of existing structure, damage mapping, photographic documentation, technical report, tests and measurements (in situ and in laboratory)
c. modeling of the structure
d. analysis of the structure: stresses - deformations, failure analysis, determination of vulnerability, verifications - conclusions concerning its response

Selection of the retrofitting intervention to be applied includes:

a. retrofitting proposals (architectural - structural), taking into consideration architectural-archaeological restrictions
b. the redesign process with the new input data (load-bearing system, actions, materials), the calculation of new stresses and deformations, failure analysis, determination of vulnerability, verifications - conclusions concerning its new response.

### *3.2. Exploitation of SMA for seismic retrofitting*

Traditional retrofitting masonry techniques such as pointing, mortar grouting or insertion of steel bars, have often proven to be inadequate in the case of historical structures, due to their possible irreversibility or to some negative side effects that may occur (i.e. incompatibility of grout resulting in material degradation and development of mechanical stresses, hindrance to natural breathing of the masonry or corrosion of steel bars). In order to prevent any damage of this kind, innovative retrofitting techniques should be applied, backed by a broad background of scientific knowledge.

In this context, considerable research has been carried out in the last years, to investigate the efficiency of SMA bars for the seismic retrofitting of historical masonries. When a structure is subjected to earthquake vibration, pre-stressed SMA bars, introduced into the load-bearing system, have the ability to dissipate seismic energy and to fasten the blocks together. SMAs also demonstrate large elastic strain capacity, excellent high/low-cycle fatigue resistance, re-centering capabilities and excellent corrosion resistance, which make them applicable for the structural protection of cultural heritage, mainly masonry, structures.

The most effective and widely used alloys include NiTi, CuAlMn and FeMn. Their properties are ought to the fact that they change their crystalline arrangement when they are stressed or heated. In their low temperature phase SMAs are in their martensitic form, which is the relatively soft and easily deformed to several percent, phase. When heated they are gradually transformed into their austenite phase which is stronger. The critical temperatures are denoted by Ms (starts the phase transformation from austenite to martensite), Mf (the phase transformation from austenite to martensite is complete), As (starts the phase transformation from martensite to austenite), Af (the phase transformation from martensite to austenite is complete).

As a result of the crystalline structure transformations, three SMA properties can be exploited for their application as seismic energy dissipative materials (Casciati, *et al.* 1998, Casciati and Faravelli 2004): a) the super-elastic effect which permits large elastic deformations followed by the recovery of the original shape upon unloading (residual strains are very small); b) the shape memory effect which involves the alloy resuming its original shape and rigidity when heated from its lower temperature phase (martensite form), to its high temperature phase (austenite form); c) the dissipation of energy through the hysteresis effect. A schematic stress-strain curve of a sample of SMA, is illustrated in Fig. 2.

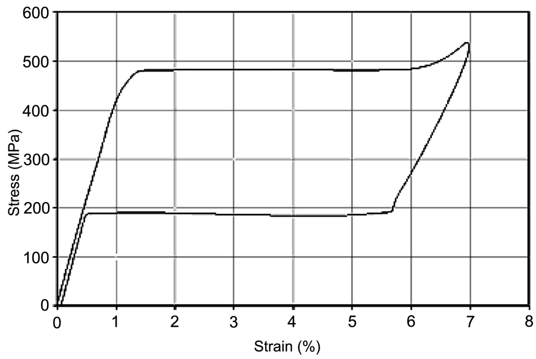



Fig. 2 Schematic stress-strain curve for a Ni-Ti SMA

SMAs bars used for the reinforcement of masonry structures are often prestressed to reach strain in the plateau (the section of the stress-strain curve where stress remains nearly constant with increasing strain). Taking into consideration that masonry is mainly vulnerable to tensile stresses during an earthquake event, the prestressing allows reaching a higher value of seismic intensity before failure occurs, than in the case of non prestressed bars. The prestressing can be effectuated using either special anchorage plates that allow a large distribution of the pretension load and avoid stress concentration, or special devices for this purpose (Auricchio, *et al.* 2001).

The application of SMA bars on a masonry historical structure varies with the particular characteristics of each structure. For the retrofit of arches, bars are usually placed between the two supporting columns, for the reinforcement of walls cross-braces are placed on the masonry plane, and for slender structures, SMA bars are usually incorporated vertically into the load bearing system.

## 4. Analytical evaluation of the retrofitting efficiency using SMA

### *4.1. Description of the case study*

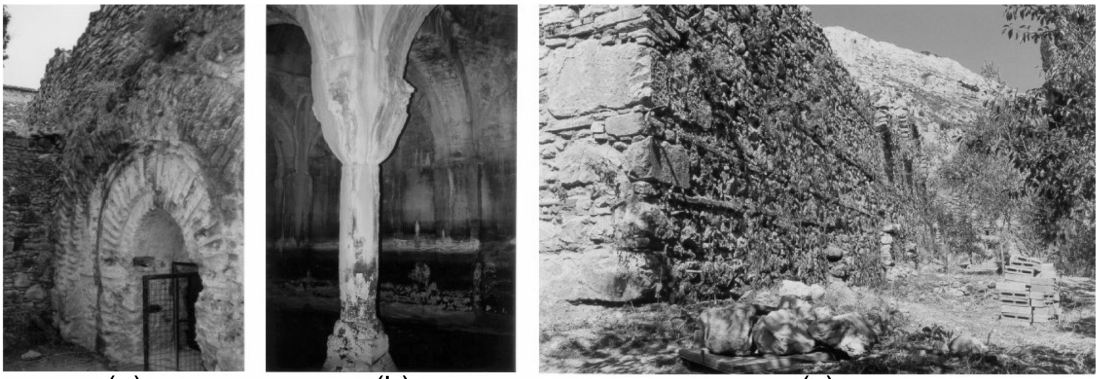
In this paper, the efficiency of SMA bars for the retrofit of historical masonry structures is evaluated through a case study, an existing historical structure. Nea Moni is a monastery situated in the Island of Chios, Greece. It has been constructed in the middle of 11th century and it is included in the Catalogue of Monuments of the International Cultural Heritage of UNESCO.

The investigated structure is the church of Agios Panteleimonas, which is connected with a semi-underground Cistern, through a common vertical wall. Both of them are masonry structures. The church has a rectangular layout of $14{,}65 \times 5{,}25\ m^2$ and is 7,30 m high. Cistern's height is 6,70 m, its length equals to 18,45 m and its width equals to 11,70 m. A vault roof based on arches covers it. The roof is supported by two series of columns. In Fig. 3, 4 and 5 the two structures and their common wall are shown.

Up to now, the structure has suffered at least one severe earthquake in 1881. Local damage and cracks are apparent. On the church walls there are extended cracks around the openings. In the interior of the Cistern the lime-cast is decayed and on the common wall of the two structures, local displacements have taken place.

Several years ago, an attempt for the structural strengthening of the Church has been made, through the insertion of steel bars perpendicular to the plane of the walls, as seen in Fig. 6. Actually, steel bars

Fig. 3 The church of agios panteleimonas



(a) (b) (c)

Fig. 4 (a) The entrance of the Cistern (b) Its interior (c) The Cistern masonry

have been corroded and creeping phenomena have been presented, resulting in the development of cracks instead of the desired structural strengthening.

### *4.2. Modelling and structural analysis*

For the analysis of the structure, a three-dimensional finite element model was constructed, using the


Fig. 5 The common vertical wall of the two structures

Fig. 6 Past intervention using steel bars

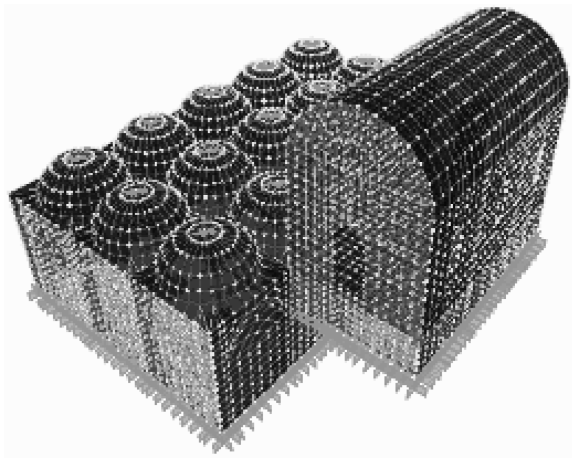


Fig. 7 Finite element model

SAP2000 v.9 software. The finite element model is presented in Fig. 7. For its discretization, shell elements have been used, activating six degrees of freedom on each node (three translational and three rotational). The two structures have been analyzed as a single model. Both structures were considered fixed at their base. The software used was SAP2000.

A homogenized isotropic material has been considered for the masonry. Its properties have been

Table 1 Masonry material properties

| Compression strength $f_{wc}$ | Modulus of Elasticity | Weight $\gamma$ | Poisson's ratio |
|---|---|---|---|
| (MPa) | (GPa) | (KN/m$^3$) | |
| 1,55 | 1,55 | 22 | 0,3 |

estimated based on blocks (bricks and natural stones) and mortar properties. Masonry tensile strength has been calculated as a percentage of mortar strength in tension, the value of which presents considerable dispersion. Masonry tensile strength was estimated between 100 $\div$ 300 KPa. The rest of the material properties have been considered constant and they are seen in Table 1.

For the simulation of the applied actions on the structure the following static and dynamic loadings have been considered:

- permanent loads
- static soil pressure applied on the external part of underground walls
- hydrostatic pressure applied on the internal part of Cistern walls, up to the water surface -seismic actions that consist of:
  i. seismic inertia forces applied on both structures
  ii. dynamic soil pressure applied on the external part of underground walls (calculated as superadded static soil pressure)
  iii. hydrodynamic pressure applied on the internal part of Cistern walls up to the water surface

Two types of seismic loading were considered: a) 4 response spectrum functions (according to the response spectrum suggested by the Greek Aseismic Code), for peak ground accelerations (PGA) equal to 0,12 g, 0,16 g, 0,24 g and 0,36 g to perform response spectrum analysis and b) the accelerogram of the Athens earthquake (1999) to perform time-history analysis.

### 4.3. Evaluation of the actual state of the structure

For the evaluation of the seismic response of the structure, before proceeding with any retrofitting measures, an estimation of structural failure has been made using the methodology described in paragraph 2.3. Parametric results were obtained for all discrete values of PGA and masonry strength in tension. An indicative output of the software FAILURE is presented in Fig. 8, for the projection of the Cistern roof, for a PGA equal to 0,24 g. Its damage is extensive.

In addition to this, the quantitative calculation of the seismic vulnerability of the structure was performed. For this purpose, the percent of the wall surface that has failed has been calculated for the

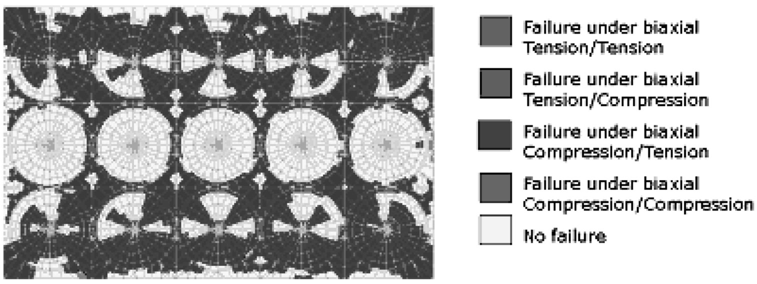



Fig. 8 Failure output for the cistern roof projection

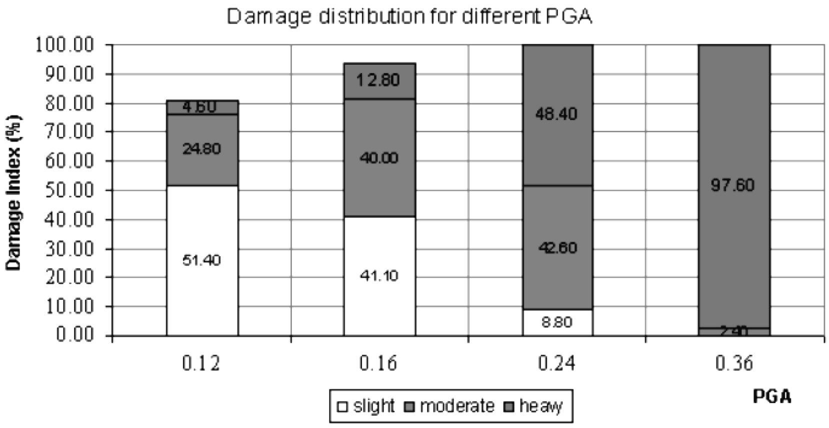



Fig. 9 Seismic vulnerability evaluation for the actual state

structure, for all parameter combinations. The distribution of this damage index (varying according to masonry strength in tension) was considered to follow the normal probability density function.

For the qualitative description of the extent of damage, the thresholds for the damage index are: 0-20% for slight damage, 20%-35% for moderate damage, >35% for heavy damage. The results are shown in Fig. 9.

### *4.4. Evaluation of retrofitting using SMA bars*

For the seismic retrofitting of the Church and the Cistern, an innovative technique has been proposed, involving the use of SMA prestressed bars for the passive control of the structure through the dissipation of seismic energy. Bars were placed horizontally, in two directions under the arches of the Cistern and in one direction under the Church roof (Fig. 10).

For the retrofitting using SMA bars, NiTi SMAs have been considered. For the quantification of their damping properties, their energy dissipation capacity, resulting from their hysteresis loop has been considered (Van der Eijk, *et al.* 2004).

For the evaluation of the efficiency of the retrofitting technique, a non-linear time history analysis has

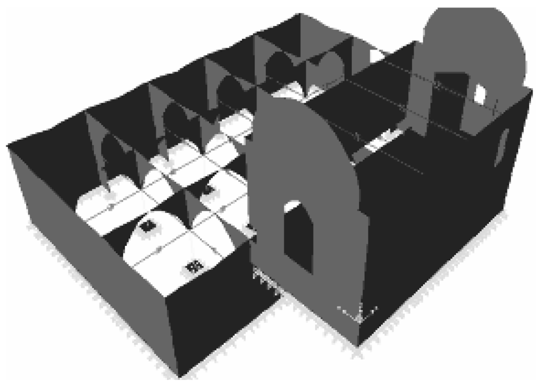


Fig. 10 Placement of SMA bars

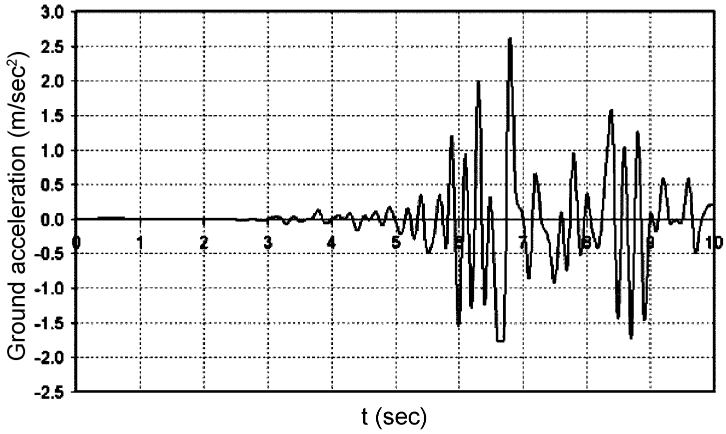



Fig. 11 The Athens earthquake accelerogram (1999)

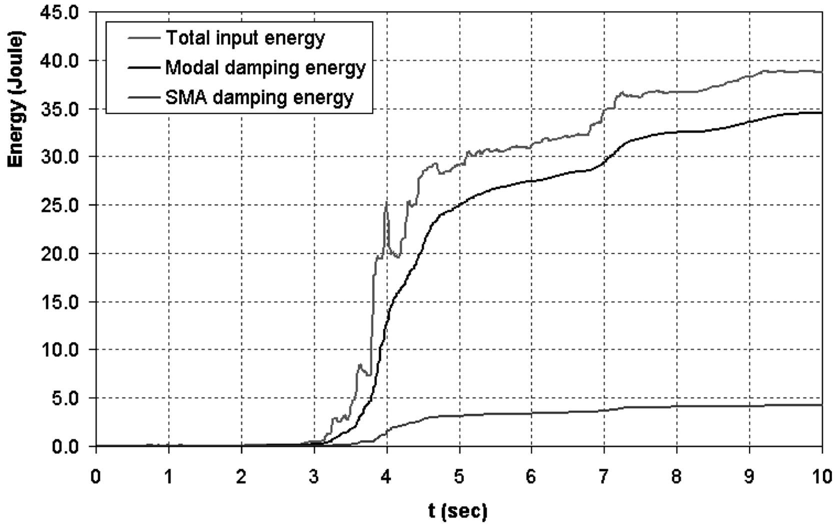



Fig. 12 Energy balance for the retrofitted structure with SMA

been performed for the accelerogram of Athens earthquake (1999), which is presented in Fig. 11.

In Fig. 12 three lines are depicted. The higher one is the total input seismic energy and the second lower line is the modal damping energy. The difference between the two lines, at every moment, represents, approximately, the energy dissipated by SMA bars, which equals to 10% of the total input seismic energy.

## 5. Conclusions

In this paper, the aseismic protection of historical structures, using innovative retrofitting techniques, has been discussed.

For this purpose, firstly, a methodology has been presented for the evaluation of the seismic response of historical masonry structures. The methodology involves the assessment of failure occurring on the masonry surface, due to the seismic ground motion, as well as the vulnerability evaluation taking into consideration simulation uncertainties (concerning mainly seismic intensity and masonry properties).

The properties of SMA that can be exploited for the seismic retrofitting of historical masonry structures have been discussed, involving, among others, their capability to dissipate seismic energy following the transformation of their crystalline structure.

The investigation of the seismic response of a case study, a Byzantine church and a Cistern at Nea Moni of Chios, a monument protected by UNESCO, has been performed. For this purpose the finite element method was used, as well as the proposed methodologies for failure and vulnerability assessment. The retrofitting of the case study has been investigated using prestressed SMA bars. Time history results revealed the effective dissipation of seismic energy by SMA bars.

## Acknowledgements

This paper has been elaborated within the frame of the European project WINDCHIME: Wide-Range Non-intrusive devices toward Conservation of Historical Monuments in the Mediterranean Area.

## References

Auricchio, F., Faravelli, L., Magonette, G. and Torra, V. (2001), "Shape memory alloys. advances in modelling and applications", International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain.

Caciati, F., Faravelli, L. and Petrini, L. (1998), "Energy dissipation in shape memory alloy devices", *Comput. Aided Civ. Infrastr. Eng.*, **13**, 433-442.

Casciati, S. and Faravelli, L. (2004), "Thermo-mechanic characterization of a cu-based shape memory alloy", *Proc. of International Symposium on Network and Center-Based Research for Smart Structures Technologies and Earthquake Engineering*, Tachibana, Spencer and Mukai (eds.), Osaka Univ., Suita, Osaka, Japan, 377-388.

Desroches, R. and Smith, B. (2003), "Shape memory alloys in seismic resistant design and retrofit: a critical assessment of the potential and limitations", *J. Earthq. Eng.*, **7**(3), 1-15.

SAP 2000, v.9 Manual Syrmakezis, C. A., Asteris, and P.G. (2001), "Masonry failure criterion under biaxial stress state", *J. Mater. Civ. Eng.*, ASCE, **13**(1), 58-64.

Syrmakezis, C.A., Antonopoulos, A.K. and Mavrouli, O.A. (2005), "Historical structures vulnerability evaluation using fragility curves", *Proc. of the Tenth International Conference on Civil, Structural and Environmental Engineering Computing*, Rome, Italy, 29 August-2 September.

Van der Eijk, C., Akselsen, O. M. and Zhang, Z. (2004), "Seismic dampers based on NiTi shape mamory alloys. a state-of-the-art on metallurgy and modelling", Wind-Chime project, Deliverable 1, Report no STF80 F04048 SINTEF.

*FC*