PAPER REF: 6316

# A Stochastic Computational Framework for the Seismic Assessment of Monumental Masonry Structures

**Panagiotis G. Asteris[1], Maria Douvika[1], Panagiotis Karakitsios[2], Petros Moundoulas[3†], Maria Apostolopoulou[3], Antonia Moropoulou[3]**

[1] Computational Mechanics Laboratory, School of Pedagogical and Technological Education, Athens, Greece
[2] Department of Civil Engineering, National Technical University of Athens, Athens, Greece
[3] Laboratory of Materials Science and Engineering, School of Chemical Engineering, National Technical University of Athens, Athens, Greece

## ABSTRACT

Masonry structures are complex systems that require a thorough and detailed knowledge and information regarding their behaviour under seismic excitations. Appropriate modelling of a masonry structure is a prerequisite for a reliable earthquake resistant design or assessment. However, modelling a real structure to a robust quantitative (mathematical) representation is a very difficult, complex and computationally demanding task. The paper herein presents a new stochastic computational framework for earthquake resistant design of masonry structural systems, based on the probability behaviour of the crucial parameters involved in the modelling of the structure such as material strength and seismic characteristics via fragility analysis. The application of the proposed methodology is illustrated in the case study of a historical and monumental masonry structure, namely, the assessment of the seismic vulnerability of the Kaisariani Monastery, a byzantine church which was built in Athens, Greece at a time period spanning the end of the 11th to the beginning of the 12th century. Important conclusions have been derived regarding the effectiveness of the intervention techniques used for the reduction of the vulnerability of the case-study structure, by comparing the results obtained.

**Keywords:** historical structures, fragility curves, masonry retrofitting, mortars, structural assessment, structural modelling

## INTRODUCTION

There are many historic monuments of high architectural and cultural value around the world that deserve protection against major earthquakes. The purpose of investigating the seismic behavior of ancient monuments such as masonry structures is twofold, namely: (1) to select the suitable and effective rehabilitation techniques, and (2) to identify the mechanisms that have allowed the surviving monuments to avoid structural collapse and destruction during strong earthquakes.

Both the above mentioned aspects are of great interest to the engineering profession as well as to the educational procedure in engineering faculties. To this, one might add the need for multidisciplinary cooperation based on the principles imposed by past or current regulations and scientific Charters [e.g. the Athens Charter 1931 (ICOMOS 1931), the Venice Charter 1964 (ICOMOS 1964), etc.], which make the whole process of analysis more demanding.

Our research has adopted the core values embedded in the international standards, delineated by the principles of research and documentation, authenticity and integrity, compatibility (both visual and physical and/or chemical), minimal intervention and the degree of reversibility (as it is very seldom possible to achieve a fully reversible technique). It should also be mentioned that the prior knowledge of (other) experts dealing with the modeling, the assessment of seismic vulnerability and the restoration techniques, has provided an essential input to our effort. Detailed and in-depth state-of-the-art reports can be found in Syrmakezis *et al.* 1995 and 1997; Binda *et al.* 2005 and 2006; Asteris *et al.* 2005 and 2014; El-Borgi *et al.* 2008; Lourenço 2006; Asteris 2008; Onaka 2009, Pagnini *et al.* 2011; Giannopoulos and Asteris 2011; Vicente *et al.* 2011 and 2012; Figueiredo *et al.* 2013; Silva *et al.* 2014 and Panto *et al.* 2016. In particular, regarding the development of rehabilitation mortars, the state-of-the-art works (on Roman and Byzantine mortars) of Moropoulou *et al.* 2000, 2013 and 2016, have be thoroughly taken into account.

The current work presents the detailed methodology for estimating the seismic vulnerability of masonry monumental structures, as applied to the estimation of vulnerability and optimal renovation scenario for the Kaisariani Monastery's byzantine church, which was built in Athens, Greece, at the end of the 11th- to beginning of 12th-century. Emphasis has been placed to determine the construction failures by means of robust simulations, and to design the composition of rehabilitation mortars, which are ranked according to the reduction they induce to the seismic vulnerability, thus leading to selection of the optimal one.

## PROPOSED METHODOLOGY

In the framework of the above mentioned scientific Charters and classical state-of-the-art reports the proposed herein methodology consists of the following nine distinct steps:

**Step 1:** Historical and experimental documentation

There are certain aspects that should be followed before carrying out a rigorous structural analysis. In particular, experience shows that the structural analysis regarding the seismic response of a Monument is an integral part of the broader study of the Monument; history and architecture of the Monument are indispensable prerequisites for the structural analysis, in order to account for all initial and consecutive construction phases, previous interventions or additions, etc. Furthermore, results of experimental investigations regarding: geometrical data, in-situ evaluation of the strength of materials, structural properties of masonry walls, dynamic response of the construction, as well as results of possible previous monitoring can be crucial for a reliable modeling and a successful assessment of a masonry monumental structure.

**Step 2:** Material characteristics

The characteristics of materials composing the structure are basic input data for a reliable and robust structural modeling of the structure. The compressive/tensile strength of the materials, the modulus of elasticity and Poisson ratio are of primary importance, at least as far as a linear/elastic analysis is concerned. For the estimation of those parameters, combination of analytical or semi-empirical methods and experimental data (both in-situ and in-vitro) has to be employed. For the determination of the masonry compressive and tensile strength, several semi-empirical expressions are available in the literature. In the majority of these expressions, global effects contributing to the system resistance, such as buckling-effects or local-compression resistance are not considered. Detailed and in-depth state-of-the-art reports on the mechanical characteristics of masonry material, including two and three leaf stone masonry, can be found in (Tassios 1988; Tassios and Chronopoulos 1986; Asteris *et al.* 2014).

**Step 3:** Structural model

The simplest approach to the modeling of complex historic buildings is given by the application of different structural elements, employing truss, beam, panel, plate or shell elements to represent columns, piers, arches and vaults, with the assumption of homogeneous material behavior.

A 3-D finite element model (with elastic materials), such as the one used in this study,, has been considered as the most suitable for the analysis, at least as far as a global assessment is concerned. For higher model reliability, specific simulation parameters (such as the rotation capacity of the wooden floor or roof connection with the masonry wall, the degree of connections between intersected walls, the influence of spandrel beams, etc.), must always be taken into account.

**Step 4:** Actions

Different loading cases have to be taken into consideration, including seismic actions for structures built in seismic areas. Combinations of dead loads, live loads and earthquake demands, have to be used. Earthquakes have to be considered to arrive along all unfavorable directions for the building. Nevertheless, certain issues are still open, regarding e.g. the poor hysteretic behavior of masonry or the adverse influence of the simultaneous vertical component of the seismic action.

**Step 5:** Analysis

Using input data of the previous steps, a Finite Element Analysis has been performed and stresses (normal-shear) - displacements at the joints of the mesh have been calculated. Due to the actual behavior of plain masonry and the high degree of uncertainty in the previous steps, elastic analysis is a valuable tool for such structures, especially before any repair and/or strengthening.

**Step 6:** Failure criterion and Damage indices

A failure criterion must be established for the definition of the damaged regions of the structure (as a first insight). Taking into account the conclusions of Step 2 regarding materials' characteristics, such a criterion has been proposed and will be used as an input to carry out the analysis.

These failure results are used as input data for the development of a damage index. Based on this index the possibility of a structure to be damaged beyond a specified level (classified as heavy, moderate, or insignificant) for various levels of ground acceleration is determined. This information is important during the analysis and redesign process for a historical structure since it gives the opportunity to investigate different scenarios with different options regarding repair/strengthening.

**Step 7:** Seismic vulnerability assessment

Based on the damage indices computed in the previous step a quantification of the seismic vulnerability can be achieved. For the assessment of the capacity of the structure a number of techniques have been proposed. Take into account that a plethora of parameters involved in the modeling of structure depict probabilistic nature (e.g. materials characteristics and loadings- seismic excitations), the most suitable, reliable and robust technique for masonry structure seems to be a probabilistic assessment which can be achieved through fragility analysis.

**Step 8:** Repairing and/or strengthening decisions and reanalysis

According to the results of Steps 5 and 6, all the damaged regions are repaired and/or strengthened. The method to be used, the extent of the interventions, the type of the materials, etc., could be directly related to the results and are based on semi-empirical expressions for the final mechanical characteristics of masonry.

Last, a new structural analysis has to be performed including all the final materials, loading and structural data. Results of the analysis have subsequently had to be used in the process of Steps 5 to 7, leading to a final approval (or rejection) of the decisions already taken for repair or strengthening of the existing structure.

**Step 9:** Explanatory report

The last step, as a result of the proposed methodology, includes the detailed ‘Explanatory Report’, where all the collected information, the diagnosis (including the safety evaluation), and any decision to intervene should be fully detailed. This document is essential for eventual future analyses and interventions’ measures in the structure.

## FAILURE CRITERION

A key point to a successful application of the proposed methodology is the use of a reliable failure criterion for the modelling of the masonry failure. To this end, a tensor polynomial has been used for the modeling of the masonry failure. In particular, according to this criterion, the masonry material is assumed to exhibits distinct anisotropic nature and the failure surface can be described by the following equation:

$$f(\sigma) = F_i\sigma_i + F_{ij}\sigma_i\sigma_j + F_{ijk}\sigma_i\sigma_j\sigma_k + \cdots \begin{cases} \langle\ 1\ \textit{no failure} \\ = 1\ \textit{failure} \\ \rangle\ 1\ \textit{exceeded failure} \end{cases}$$

where i, j, k= 1, 2,..., 6. $F_i$, $F_{ij}$ and $F_{ijk}$ are (strength) tensors of the second, fourth and sixth rank, respectively.

Based on the above equation, restricting the analysis to a plane stress state and, assuming that a cubic formulation is a reasonably accurate representation of the failure surface and by taking into consideration the symmetry and anisotropic nature of the material (Syrmakezis and Asteris 2001; Asteris 2010 and 2013), the masonry failure surface can be expressed by the following equation (1):

$$\begin{aligned} f(\sigma_x, \sigma_y, \tau) = {} & 2.27\sigma_x + 9.87\sigma_y + 0.573\sigma_x^2 + 1.32\sigma_y^2 + 6.25\tau^2 - 0.30\sigma_x\sigma_y + \\ & 0.009585\sigma_x^2\sigma_y + 0.003135\sigma_x\sigma_y^2 + 0.28398\sigma_x\tau^2 + 0.4689\sigma_y\tau^2 = 1 \end{aligned} \quad (1)$$

or by using the dimensionless terms $\left( \bar{\sigma}_x = \frac{\sigma_x}{f_{wc}^{90^\circ}},\ \bar{\sigma}_y = \frac{\sigma_y}{f_{wc}^{90^\circ}},\ \bar{\tau} = \frac{\tau}{f_{wc}^{90^\circ}} \right)$ the above equation can be written in the form of:

$$\begin{aligned} & 17.15\,\bar{\sigma}_x + 74.57\,\bar{\sigma}_y + 32.71\,\bar{\sigma}_x^2 + 75.34\,\bar{\sigma}_y^2 + 356.74\bar{\tau}^2 + \\ & -17.12\,\bar{\sigma}_x\bar{\sigma}_y + 4.13\,\bar{\sigma}_x^2\,\bar{\sigma}_y + 1.35\,\bar{\sigma}_x\,\bar{\sigma}_y^2 + 122.46\,\bar{\sigma}_x\bar{\tau}^2 + \\ & + 202.20\bar{\sigma}_y\bar{\tau}^2 = 1 \end{aligned} \quad (2)$$

Figure 1 shows the graphical representation of equation (2) in normal stress terms.

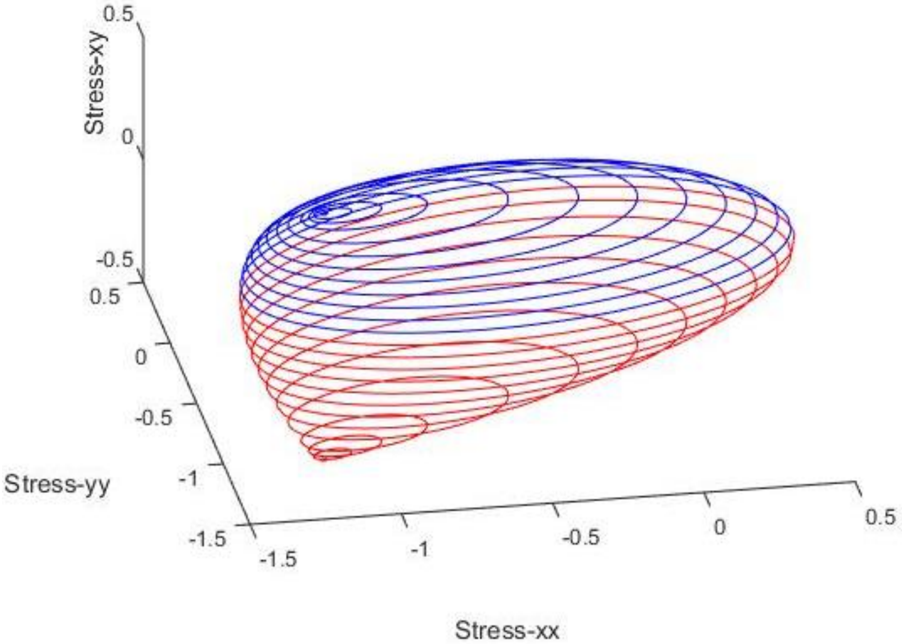


Fig. 1 Failure surface in non-dimensionless normal stress terms

## DAMAGE INDEX

Damage control in a building is a complex task, especially under seismic action. There are several response parameters that can be instrumental in determining the level of damage that a particular structure suffers during a ground motion; the most important ones are: deformation, relative velocity, absolute acceleration, and plastic energy dissipation (viscous or hysteretic). Controlling the level of damage in a structure consists primarily in controlling its maximum response. Damage indices establish analytical relationships between the maximum and/or cumulative response of structural components and the level of damage they exhibit (Park *et al.*, 1987). A performance-based numerical methodology is possible if, through the use of damage indices, limits can be established to the maximum and cumulative response of the structure, as a function of the desired performance of the building for the different levels of the design ground motion. Once the response limits have been established, it is then possible to estimate the mechanical characteristics that need to be supplied to the building so that its response is likely to remain within the limits.

For the case of masonry structures a new damage index is proposed which employs as the response parameter the percentage of the damaged area of the structure relatively to the total area of the structure. The proposed damage index [DI], for a masonry structure can be estimated by the following equation (3):

$$[DI] = \frac{A_{fail}}{A_{tot}} \times 100 \tag{3}$$

where $A_{fail}$ is the damaged surface area of the structure and $A_{tot}$ is the total surface area of the structure.

## STRUCTURAL PERFORMANCE LEVELS

As practiced today, performance-based seismic design is initiated with an interplay between demands and appropriate performance objectives. The Engineer then has to develop a design capable of addressing these objectives. Performance objectives are expressed as an acceptable level of damage, typically categorized as one of several performance levels, such as immediate occupancy, life safety or collapse prevention, given that ground shaking of specified severity is experienced.

In the past, the practice of meeting performance-based objectives was included in design practice, but it was rather informal simplistic and non-standard. Some Engineers would characterize performance as life-safety or not; others would assign ratings ranging from poor to good. This qualitative approach adopted for performance prediction was appropriate given the limited capability of seismic-resistant design technology to deliver building designs capable of quantifiable performance.

We consider three structural performance levels, namely: a) heavy damage, b) moderate damage and c) insignificant damage, in a similar way to the Federal Emergency Management Agency (FEMA 273 1997). The performance levels are defined by the values of DI (as shown in Table 1). Especially a value of DI less than 15% can be interpreted as insignificant damage; from 15% to less than 25%, as moderate damage; and larger or equal than 25% as heavy damage. In fact, other approaches could be used, according to the recent European Codes (EC8 2005), based on a more engineered (and more detailed) estimation of damage.

Table 1: Proposed Structural Performance Levels for un-reinforced masonry

| **Overall Damage** | **Heavy Damage** | **Moderate Damage** | **Insignificant Damage** |
|---|---|---|---|
| | Extensive cracking: face course and veneer may peel off. Noticeable in-plane and out-of-plane offsets. | Extensive cracking. Noticeable in-plane offsets of masonry and minor out-of-plane offsets. | Minor cracking of veneers. Minor spalling in veneers at a few corner openings. No observable out-of-plane offsets. |
| [DI] | ≥ 25% | 15% ≤ ~ < 25% | < 15% |
| | Collapse prevention | Life safety | Immediate occupancy |

## FRAGILITY ANALYSIS

One of the problems to be faced and resolved at later stages of the global analysis has to do with the quantitative vulnerability assessment of the building as it is (damaged or not) as well as if it will be “modified” after interventions. In other words, a method is needed to assess the seismic vulnerability of the existing structure as well as to assess the intervention scenarios ranked them according to the reduction they induce to the seismic vulnerability, thus leading to selection of the optimal one. One of the most important tools is the fragility analysis, which provides a measure of the safety margin of the structural system above specified structural performance/hazard levels.

Evaluating seismic fragility information curves for structural systems involves: a) information on structural capacity, and b) information on the seismic hazard. Due to the fact that both the aforementioned contributing factors are uncertain to a large extent, the fragility evaluation cannot be carried out in a deterministic manner. A probabilistic approach, instead, needs to be utilized in the cases in which the structural response is evaluated and compared against “limit states” that is, limiting values of response quantities correlated to structural damage.

Fragility is evaluated as the total probability of a response parameter R exceeding the allowable response value $r_{\lim}$ (limit-state), for various earthquake intensities I. In mathematical form, this is simply a conditional probability (Barron-Corvera, 2000, Reinhorn et al., 2001) given bythe following equation 4:

$$Fragility = P\left[R \geq r_{\lim} \middle| I\right] = \sum_{j}^{3} P\left[R \geq r_{\lim} \middle| I, C\right] P\left(C = c_j\right) \tag{4}$$

where $P(C = c_j)$ is the probability that capacity $c_j$ occurs. In the following examples basic steps for the development of the fragility curves, are shortly presented.

## CASE STUDY

In this section, the reliability, the effectiveness and the robust of the methodology, for the assessment of the seismic vulnerability of monumental masonry structure, is presented through a step-by-step approach. In particular, the proposed methodology has been applied to a historical and monumental masonry structure in Athens, Greece.

**Identity of the structure:** The structure under investigation is the Kaisariani Monastery, a byzantine church (Figure 2) which was built in Athens, Greece at the end of the 11th- to beginning of 12th-century. Moreover, the site has a far longer history as a cult center: in Antiquity, it was probably a site dedicated to Aphrodite, before being taken over by Christians in the 5th/6th centuries. Remains of a large early Christian basilica lie to the west, over which a smaller church was built in the 10th/11th centuries (Papadopoulou 2001 & Salemi 2001).

Fig. 2 Front façade of the Kaisariani monastery

**Material characteristics:** A number of historic mortar samples were obtained internally and externally of the main temple, from different sides and depths of the walls. Two brick samples were obtained, the first one as a concrete peeled portion of brick from the eastern side of the cloisonné and the second one is a piece of brick from the same area. The lab techniques applied in order to characterize and study the structural materials of the Catholicon were Fiber Optic Microscopy (FOM), Grain Size Distribution Analysis, Differential Thermal and Thermo-Gravimetric Analysis (DTA-TG), X-ray diffraction (XRD), Mercury Intrusion Porosimetry (MIP), Total Soluble Salts Measurements, as well as Water Absorption by Capillarity test in order to estimate the capillarity absorption coefficient. Based on the results deriving from the above techniques, it has been concluded that the mortars of Catholicon of Kaisariani Monastery are lime mortars mixed with calcite and aluminosilicate aggregates, with high porosity values and occasionally the addition of straw or fiber admixtures. The microstructural characteristics of the examined bricks are typical for handmade bricks of the byzantine period. The elevated presence of salts and in particular nitrates must be taken into consideration when selecting a proper restoration mortar.

**Structural modeling:** The program used to simulate the structure is the software SAP2000 v14 Nonlinear. With this software, an appropriate FEM model to calculate the response of the structure was formed. The development of the finite elements mesh was such that the ideal concentration of masses at the nodes simulates well the real mass distribution. This ensures a reliable simulation of the inertial loads for dynamic analysis. To fully determine the deformation of the system, six degrees of freedom for each node were considered. The six degrees of freedom correspond to three translations, along the axes x, y, z and three rotations of vectors, parallel to the same axes. The model of the building is shown schematically in Figure 3.

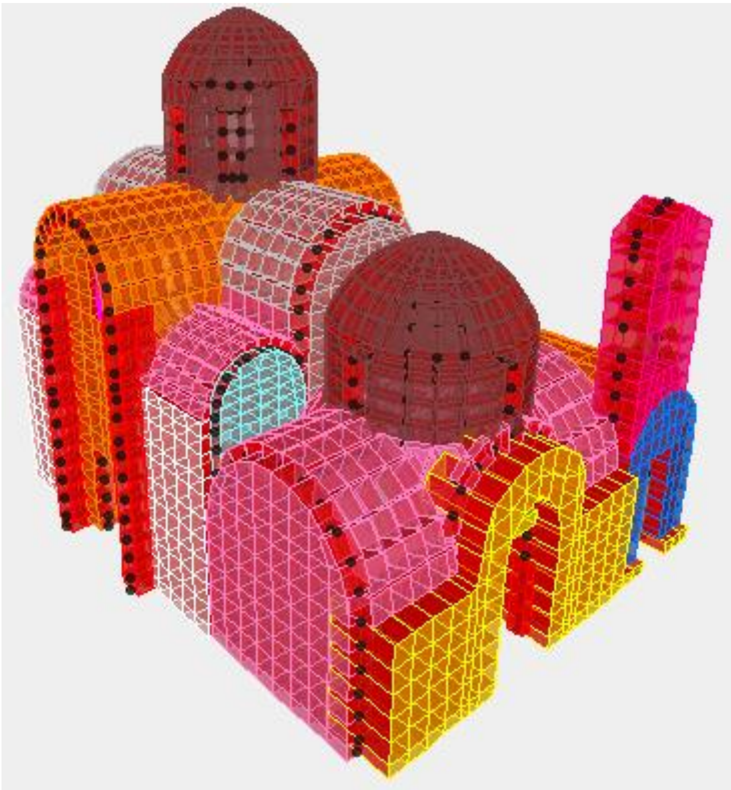

Fig. 3 Finite element modeling of the Kaisariani monastery

The geometrical simulation was done by isotropic surface members (shell elements) and isotropic linear members (frame elements), which are considered to represent with sufficient reliability the properties of the real body. The model used to analyze the building is spatial. The discretization of the finite element mesh was through flat quadrilateral and triangular elements. For the simulation model 3.548 nodes and 3.445 surface elements were used.

**Interventations scenarios:** Based on the results of the study and characterization of historic mortars, the available literature was examined in order to select proper restoration mortars. The restoration mortars must fulfill compatibility criteria regarding the physicochemical and microstructure characteristics of the original materials. In the case of Kaisariani monastery, the restoration mortars must have properties within or close to the range of acceptability limits for typical lime mortars, as proposed by Moropoulou and Bakolas (1998). Lime-metakaolin mortars show a very good agreement with the aforementioned attributes. Furthermore, lime-metakaolin mortars can achieve a wide range of mechanical strength properties depending on the addition of metakaolin in the mortar mix (Bakolas et al. 2006, Moropoulou *et al.* 2006). The low mechanical properties of the foccileferous stone of Kaisariani Monastery demands the use of a restoration mortar with compressive strength values lower or even to 8.2 MPa, as tested with a portable rebound hammer (Moropoulou *et al.* 2015). The use of fragility curves can serve as a tool to examine the serveacibility of the proposed mortars and the selection of the optimum scenario, regarding the contribution of the restoration mortar to the mechanical strength of the historical masonry.

**Damage indices:** The failure analysis for the existing structure as well as for the studied interventions' scenarios was based on the failure criteria explained in previous sections. In addition to the main computer program used for the analysis (SAP2000), a special computer program, capable of producing a "visual" representation of the failed regions within the structure, has been developed from scratch. The program takes the SAP2000 analysis results as input and gives statistics for the number of failure points, as well as of the type of failure, providing a general view of the probable damage level and the main type of damages within the structure. Based on these results and using the equation 5 the damage indices have defined for a range of Peak Ground Accelerations between 0.08g to 0.40g and masonry tensile strength ranging from 50 kPa to 324 kPa.

**Fragility Curves:** The results concerning the damage indices of the structure were analyzed with probabilistic methods. In particular, the Probability Distribution Function and the associated Probability Density Function were estimated for each level of Peak Ground Acceleration applied at the structure. Using these Probability Distribution Functions, the probabilities of structure damage for the three structural performance levels (insignificant, moderate and heavy damage) have been determined and the results, both for existing and repaired structures, are presented in Table 2 for normal distribution.

Figures 4, 5 and 6 show the fragility curves of the structure before and after interventions for each one structural performance level for the case of normal distribution. These figures show that the fragility curves are important tools in evaluating and ranking the efficiency of the remedial proposals, to address the seismic protection of masonry structural systems. It should be indicatively mentioned that the probability of heavy damage from a seismic motion with demand represented by PGA=0.24g is reduced by 35 and 70 % for the repaired structure with restoration mortars M5 and M10 respectively.

Table 2: Probability of exceeding the damage state for the structure before and after interventions (Normal Distribution)

| Case | Damage state | Peak Ground Acceleration (PGA) (g) | | | | |
|---|---|---|---|---|---|---|
| | | **0.08** | **0.16** | **0.24** | **0.32** | **0.40** |
| Existing Structure | Insignificant | 0.70 | 0.92 | 0.99 | 1.00 | 1.00 |
| | Moderate | 0.49 | 0.81 | 0.97 | 1.00 | 1.00 |
| | Heavy | 0.28 | 0.64 | 0.90 | 0.98 | 1.00 |
| Repaired Structure with Mortar M5 | Insignificant | 0.42 | 0.80 | 0.92 | 0.99 | 1.00 |
| | Moderate | 0.06 | 0.52 | 0.79 | 0.94 | 0.99 |
| | Heavy | 0.00 | 0.23 | 0.58 | 0.83 | 0.95 |
| Repaired Structure with Mortar M10 | Insignificant | 0.00 | 0.64 | 0.80 | 0.89 | 0.99 |
| | Moderate | 0.00 | 0.18 | 0.54 | 0.74 | 0.95 |
| | Heavy | 0.00 | 0.01 | 0.26 | 0.51 | 0.87 |

## CONCLUSIONS

The vulnerability and assessment and the restoration techniques of historical masonry structures remains a considerable challenge from the engineering point view, despite the substantial effort that has taken place in research in the last three decades. In the present work, a new stochastic computational framework for earthquake resistant design of masonry structural systems has been presented, namely, the fragility analysis has been applied based on the probability behaviour of crucial parameters involved in the modelling of the structure such as the values of materials strength and peak ground acceleration.

According to the analysis of results for the strengthened structure provided here, it can be concluded that the methodology followed, has been proved helpful to the modeling and vulnerability assessment of masonry structures such as historical monuments.

Furthermore, it has been shown that the proposed approach offers a ranking method, which helps civil authorities to optimize decisions on choosing, among a plethora of structures, which ones present the higher levels of vulnerability and are in need of immediate strengthening. It also helps the practicing engineer to choose the optimal repairing scenario among a number of competing scenarios.

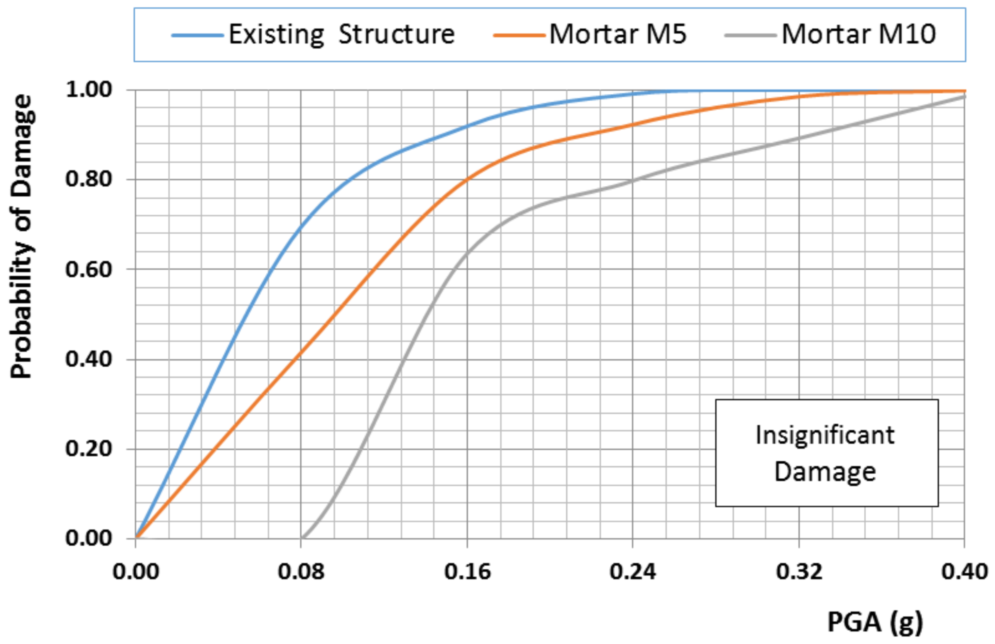


Fig. 4 Fragility curves of the structure before and after interventions (Normal distribution)

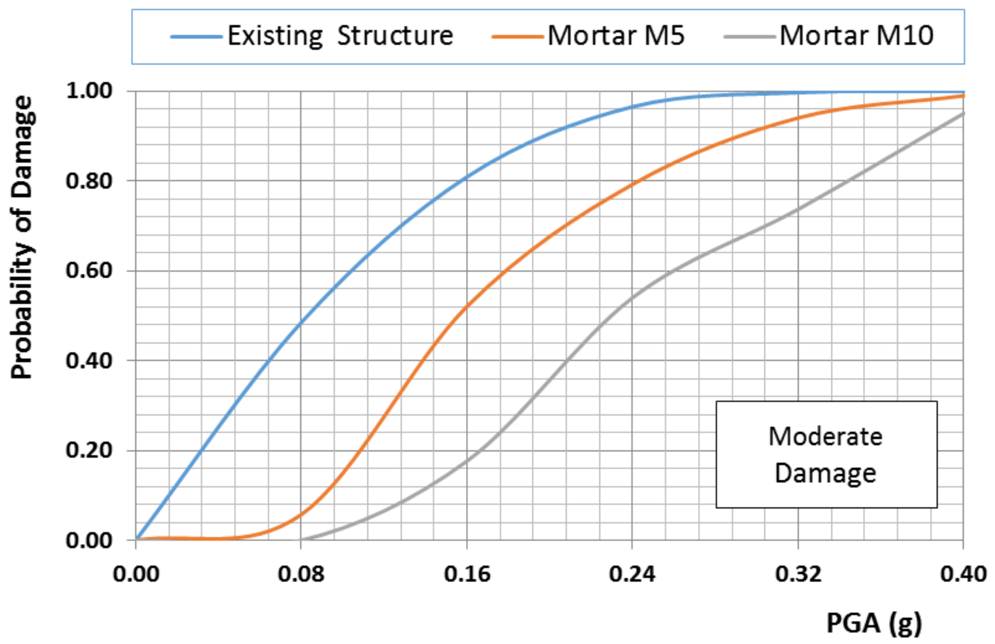


Fig. 5 Fragility curves of the structure before and after interventions (Normal distribution)

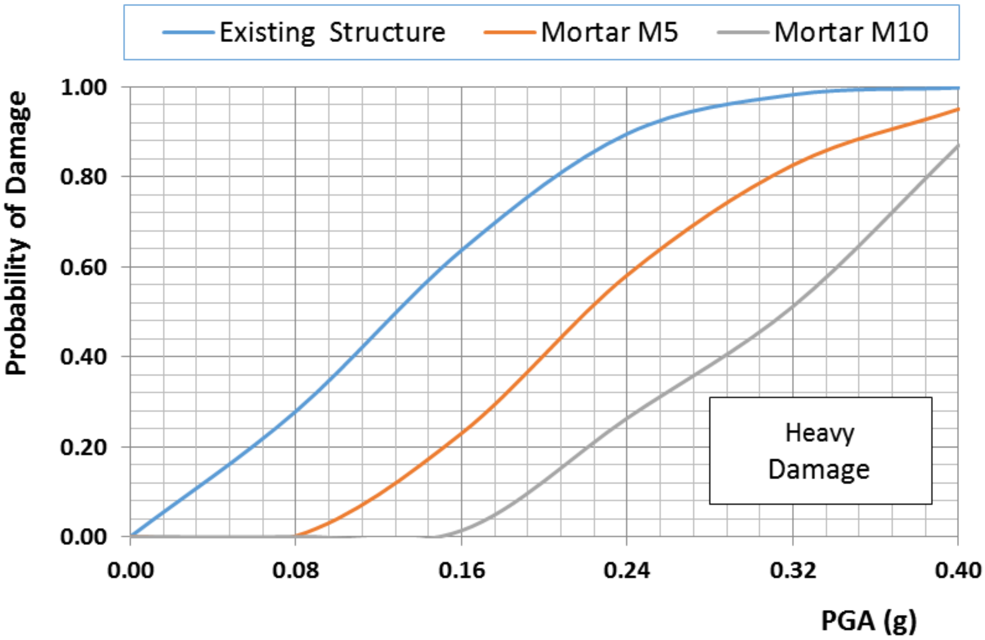


Fig. 6 Fragility curves of the structure before and after interventions (Normal distribution)

## ACKNOWLEDGMENTS

The investigation was performed within the research project "Seismic Protection of Monuments and Historic Structures - SEISMO" which is co-financed by the Greek Ministry of Education and Religions and the European Union under the action "Thales" within the context of the Operational Programme - Education and Lifelong Learning, NSRF 2007-2013.

## REFERENCES

Asteris, P.G., Tzamtzis, A.D., Vouthouni P.P., Sophianopoulos, D.S. (2005). Earthquake Resistant Design and Rehabilitation of Masonry Historical Structures. *Practice Periodical on Structural Design and Construction, (ASCE), 10*(1), 49-55.

Asteris, P.G. (2008). On the structural analysis and seismic protection of historical masonry structures. *The Open Construction and Building Technology Journal, 2*(1), 124-133.

Asteris, P.G. (2010). A simple heuristic algorithm to determine the set of closed surfaces of the cubic tensor polynomial. *The Open Applied Mathematics Journal, 4*, 1-5.

Asteris, P.G. (2013). Unified yield surface for the nonlinear analysis of brittle anisotropic materials. *Nonlinear Sci Lett A, 4*(2), 46-56.

Asteris, P.G., Sarhosis, V., Mohebkhah, A., Plevris, V., Papaloizou, L., Komodromos, P., Lemos, J.V. (2015). *Numerical Modeling of Historic Masonry Structures. Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures* (V. P. Panagiotis G. Asteris Ed.).

Asteris, P.G., Plevris, V. (2016). Anisotropic Masonry Failure Criterion Using Artificial Neural Networks. *Neural Computing and Applications (NCAA)*. doi: DOI: 10.1007/s00521-016-2181-3

Asteris, P.G., Chronopoulos, M.P., Chrysostomou, C.Z., Varum, H., Plevris, V., Kyriakides, N., Silva, V. (2014). Seismic vulnerability assessment of historical masonry structural systems. *Engineering Structures, 62-63*, 118-134. doi: 10.1016/j.engstruct.2014.01.031

Bakolas, A., Aggelakopoulou, E., Moropoulou, A., Anagnostopoulou. (2006). Evaluation of pozzolanic activity and physico-mechanical characteristics in metakaolin-lime pastes. *Journal of Thermal Analysis and Calorimetry, 84*, 157-163.

Binda, L., Bosiljkov, V., Saisi, A., Zanzi, L. (2006). *Guide-lines for the diagnostic investigation of historic buildings.* Paper presented at the Proceedings of the Seventh International Masonry Conference, London.

Binda, L., Saisi, A. (2005). Research on historic structures in seismic areas in Italy. *Progress in Structural Engineering and Materials, 7*(2), 71-85. doi: 10.1002/pse.194

Eurocode 8: Design of structures for earthquake resistance -Part 3: Assessment and retrofitting of buildings En 1998-3: 2005 EN (2005).

El-Borgi, S., Choura, S., Neifar, M., Smaoui, H., Majdoub, M.S., Cherif, D. (2008). Seismic vulnerability assessment of a historical building in Tunisia. *Smart Structures and Systems, 4*(2), 209-220.

FEMA-273. NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency (1997).

Figueiredo, A., Varum, H., Costa, A., Silveira, D., Oliveira, C. (2013). Seismic retrofitting solution of an adobe masonry wall. *Materials and Structures/Materiaux et Constructions, 46*(1-2), 203-219.

Giannopoulos, I.P., Asteris, P.G. (2011 Earthquake resistant design of masonry structural systems, 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2011; Corfu; Greece; 25 May 2011 through 28 May 2011; Code 86982.

ICOMOS1931. (1931). *The Athens Charter for the Restoration of Historic Monuments*. Paper presented at the First International Congress of Architects and Technicians of Historic Monuments, Athens, Greece. http://www.icomos.org/athens_charter.html

ICOMOS1964. (1964). *The Venice Charter for the Restoration of Historic Monuments*. Paper presented at the Second International Congress of Architects and Technicians of Historic Monuments, Venice, Italy. http://www.international.icomos.org/charters/venice_e.htm

Lourenço, P.B. (2006). Recommendations for restoration of ancient buildings and the survival of a masonry chimney. *Construction and Building Materials, 20*(4), 239-251. doi: 10.1016/j.conbuildmat.2005.08.026

Moropoulou, A., Bakolas, A. (1998). Range of acceptability limits of physical, chemical and mechanical characteristics deriving from the evaluation of historic mortars. *PACT, J. European Study Group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology, 56*, 165-178.

Moropoulou, A., Bakolas, A., Bisbikou, K. (2000). Investigation of the technology of historic mortars. *Journal of Cultural Heritage, 1*(1), 45-58.

Moropoulou, A., Aggelakopoulou, E., Bakolas, A. (2006). *Earthquakes and monuments – The role of materials in the earthquake protection of monuments.* Paper presented at the V Int. Conf. on Structural Analysis of Historical Constructions, New Delhi.

Moropoulou, A., Bakolas, A., Moundoulas, P., Aggelakopoulou, E., Anagnostopoulou, S. (2015). Optimization of compatible restoration mortars for the earthquake protection of Hagia Sophia. *Journal of Cultural Heritage, 14*(3 SUPPL), 147-152.

Moropoulou A., Apostolopoulou M., Moundoulas P., Karoglou M., Delegou E., Lampropoulos K., Gritsopoulou M., Bakolas A. (2015). *The combination of NDTS for the diagnostic study of historical buildings: The case study of Kaisariani Monastery*. Paper presented at the COMPDYN 2015 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete Island.

Moropoulou, A., Apostolopoulou, M., Moundoulas, P., Aggelakopolulou, E., Siouta, L. Bakolas, A., Douvika, M., Karakitsios, P., Asteris, P.G. (2016). *The role of restoration mortars in the earthquake protection of the kaisariani monastery*. ECCOMAS Congress 2016, VII European Congress on Computational Methods in Applied Sciences and Engineering, 5 - 10 JUNE 2016, Crete Island, Greece.

Pagnini, L.C., Vicente, R., Lagomarsino, S., Varum, H. (2011). A mechanical model for the seismic vulnerability assessment of old masonry buildings. *Earthquake and Structures, 2*(1), 25-42.

Papadopoulou, I. (2001). *The Kaisariani Monastery a study on the restoration of the refectory wing.* (Master), National Technical University of Athens, Greece.

Park, Y.J., Ang, A.H.S., Wen, Y.K. (1987). DAMAGE-LIMITING ASEISMIC DESIGN OF BUILDINGS. *Earthquake Spectra, 3*(1), 1-26.

Panto, B., Cannizzaro, F., Caddemi, S., Caliò, I. (2016). 3D macro-element modelling approach for seismic assessment of historical masonry churches. *Advances in Engineering Software, 97*, 40-59.

Salemi, N. (2001). *Preservation and restoration of the residential quarters of the Kaisariani monastery.* (Master), National Technical University of Athens, Greece

Silva, V., Crowley, H., Varum, H., Pinho, R., Sousa, R. (2014). Evaluation of analytical methodologies used to derive vulnerability functions. *Earthquake Engineering and Structural Dynamics, 43*(2), 181-204.

Syrmakezis, C., Sophocleous, A., Asteris, P., Liolios, A.A. (1995). *Earthquake resistant design of masonry structural systems,* Advances in Earthquake Engineering, 2, pp. 717-726.

Syrmakezis, C.A., Asteris, P.G. (2001). Masonry failure criterion under biaxial stress state. *Journal of Materials in Civil Engineering, 13*(1), 58-64. doi: 10.1061/(ASCE)0899-1561(2001)13:1(58)

Syrmakezis, C.A., Asteris, P.G., Sophocleous, A.A. (1997). Earthquake resistant design of masonry tower structures. *Proceedings, 5 STREMA Conference on Structural Studies, 1*, 377-386.

Vicente, R., Rodrigues, H., Varum, H., Mendes Da Silva, J.A.R. (2012). Evaluation of strengthening techniques of traditional masonry buildings: Case study of a four-building aggregate. *Journal of Performance of Constructed Facilities, 25*(3), 202-216.

Vicente, R.S., Rodrigues, H., Varum, H., Costa, A., da Silva, J.A.R.M. (2012). Performance of masonry enclosure walls: Lessons learned from recent earthquakes. *Earthquake Engineering and Engineering Vibration, 11*(1), 23-34.