SEISMIC EVALUATION OF EXISTING MASONRY BUILDINGS: SCORING SYSTEM AND CALIBRATION

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SUMMARY

This paper presents a simple scoring system, which allows for a qualitative assessment of existing masonry buildings, subjected to seismic events. The scoring system that is calibrated through parameter analyses classifies the assessed buildings, taking into account basic structural characteristics of the structure (such as type and thickness of masonry, percentage of openings, number of storeys, etc.), the importance of each building, as well as the seismicity of the region and the soil conditions.

INTRODUCTION

Earthquakes constitute the major hazard for structures in Greece, where approximately 50% of the building stock is made of stone or brick masonry. There is a need for pre- and post-earthquake assessment of masonry structures, based on visual inspection. Actually, such a qualitative assessment of buildings allows for the most vulnerable ones to be identified; it may also assist competent authorities to prepare strategic plans for improvement of the seismic behaviour of buildings, taking into account the importance of each specific structure, as well as the available funds. It has to be noted that no scoring system is meant to substitute the design of interventions to an individual building. When the decision is taken to rehabilitate a building, analysis, dimensioning of interventions and adequate verifications should be performed.

Various systems for rapid visual screening of buildings were developed in several countries such as the USA, New Zealand, Greece, Canada and Italy (summarized in [1]). A procedure for rapid visual screening (RVS) was first proposed in the USA in 1988, which was further modified in 2002 [2 and 3]. This RVS procedure has been widely used in many other countries after suitable modifications (India's example in [4]). The system proposed by FEMA is applicable to various types of buildings, such as RC, wooden frame, steel frame, and masonry buildings. The most important feature of the FEMA procedure is that it permits vulnerability assessment based on walk-around of the building. However, as far as masonry structures are concerned, very few characteristics of the specific structural system are taken into account, in particular whether the masonry is reinforced or not and the existence of rigid diaphragms.

The scoring system presented in this paper, applicable only to masonry buildings, was developed within the framework of a strategic plan (National Program of Seismic

Strengthening of Existing Structures) in progress, on an initiative of the Technical Chamber of Greece. One of the actions undertaken within this plan is the vulnerability assessment of the building stock using simple screening systems developed for this purpose.

DESCRIPTION OF THE SCORING SYSTEM

The assessment of the building is based on three major factors, namely:
(a) Factor "R", depending on the resistance of the structure,
(b) Factor "H", which estimates the seismic hazard and
(c) Factor "A", that takes into account the importance of the building.
An indicative value of the vulnerability of the building "δ" is calculated as a function of factors (a), (b) and (c). It has to be noted that the vulnerability factors calculated using the proposed scoring system should not be considered as direct assessment of the seismic performance of buildings. They should rather be used as a means for identifying the most vulnerable structures out of a stock of structurally similar buildings or those that are in need of a more refined assessment. In what follows, the parameters used to formulate factors "R", "H" and "A" are described.

Factor "R": Resistance of the Building

Table 1 summarizes the parameters that contribute to the resistance of the structure. They can be subdivided into two categories, namely in parameters regarding the resistance of individual structural members and those depending on the degree of connection and interaction between structural elements.
It should be noted that the parameters that contribute to the seismic resistance of a building are not independent of the structural system. In the formulation of the present scoring system, structural characteristics of masonry structures typical for Greece were taken into account.

1	Type of material (m)*/ wall thickness (b_w) [in m] / number of stories (n)	$\beta = m * \frac{b_w}{n}$	$\beta > 0,15$ $0,15 \geq \beta > 0,10$ $\beta \leq 0,10$	r_1=	1,00 0,80 0,60
2	Total width of openings normalized to the entire length of the perimeter of the building		<0,30% 0,30%-0,40% 0,40%-0,50% >0,50%	r_2=	1,00 0,80 0,70 0,60
3	Are there openings at less than 1m from the corners of the building? (<)		no yes	r_3=	1,00 0,70
4	Existing damages		no light heavy	r_4=	1,00 0,70 not applicable
5	Connection of intersecting walls		yes, at both ends yes, at one end No connection	r_5=	1,00 0,60 0,50
6	Distance between transverse walls		<4m 4m-6m >6m	r_6=	1,00 0,70 0,50

7	Tie-beams are provided at	floor and lintel levels floor levels lintel levels none	r_7=	1,00 0,80 0,70 0,50
8	Rigid diaphragms at	floors and roof levels floor levels none	r_8=	1,00 0,70 0,50
*the parameter m takes the following values: cut natural stones: m=1,30 rubble stones: m=1,00 bricks: solid m=1,00 bricks: perforated m=0,80 Note: in case of poor connection between the stones or poor quality of mortar the values of "m" are reduced by 0,25				

Table 1. Parameters taken into account for the calculation of factor "R"

The contribution of each parameter to the resistance of the entire building is calculated by multiplying the value "r_i" with a relevant weighing factor "p_i" (see Table 2).

i=1	2	3	4	5	6	7	8
pi=0,20	0,15	0,05	0,05	0,10	0,05	0,20	0,20

Table 2. Weighing factors «p_i»

Thus, the value of the factor "R" is calculated using the following expression:

$$R = \sum_{i=1}^{8} r_i \times p_i \tag{1}$$

Factor "H": Seismic Hazard

The parameters taken under consideration in order to estimate the possible seismic hazard are shown in table 3.

1	Seismicity of the region and soil conditions	Seismicity of the region*	III II I	h_1=	3,0s 2,0s 1,5s	Where "s" depends on soil conditions
		Soil conditions**	A B C D		s=0,70 s=1,00 s=1,30 not applicable	
2	Adjacent buildings with different number of storeys ($n-n_{adj.}$)=		0 1 2	h_2=		0,00 0,50 1,00
* III, II and I correspond to the three seismicity regions, as set in the current Greek Aseismic Code (EAK 2000) [5] **A,B,C and D correspond to the four categories of soil, according to (EAK 2000)						

Table 3. Parameters taken into account for the calculation of the factor "H"

Here again, the contribution of each parameter "h_j" is allotted a weighing factor p_j (see table 4).

j=1	2
p_j=0,80	0,20

Table 4. Importance coefficients p_j

Thus, the value of the factor "H" is calculated using equation (2):

$$H = \sum_{j=1}^{2} h_j \times p_j \qquad (2)$$

Factor "A": Importance of the Building

The parameters that are considered in order to estimate the importance of the building are shown in table 5.

1	Number of visitors per day	<10 10-50 50-150 >150	a_1=	1,00 1,30 2,00 2,50
2	Total area of the building	<100m^2 100-1000m^2 >1000m^2	a_2=	1,00 1,50 2,00
3	Does the building host important administrative functions?	yes no	a_3=	2,00 1,00
4	Does the building belong to the built cultural heritage?	yes no	a_4=	1,50 1,00

Table 5. Parameters taken into account for the calculation of the importance factor "A"

The value of each parameter "a_k" is multiplied with a weighing factor p_k (see table 6).

k=1	2	3	4
p_k=0,30	0,30	0,25	0,15

Table 6. Weighing factors p_k

Thus, the factor "A" is calculated using equation (3):

$$A = \sum_{k=1}^{4} a_k \times p_k \qquad (3)$$

Finally, the vulnerability index "δ" of the building is calculated by equation (4):

$$\delta = \left(\frac{H}{R} - k_2 \right) \times A \times k_1 \qquad (4)$$

where k_2 (~0,80) is meant to cover the uncertainties related to the estimated values of various parameters and k_1 (=0,10) divides the δ-value to allow the vulnerability index to be expressed in values ranging between 1% to 100% .

CALIBRATION OF THE SCORING SYSTEM

The presented scoring system was calibrated by means of parameter analyses [6]. The main aim of the analyses that were carried out was to assess and calibrate the parameters related to the resistance of the structure (described in Table 1). For this purpose, a variety of models (from single free standing walls with or without portions of transverse walls to entire two storey buildings) was analyzed under in-plane and/or out-of-plane actions. In order to yield results that allow for comparison between various models, two alternative load cases are examined, namely: (a) Uniformly distributed horizontal load equal to $10kN/m^2$ and (b) Different value of uniformly distributed horizontal load for each model. In this case, the imposed load is selected so that to yield approximately equal stresses in all models, in the regions that are considered as critical for their overall behaviour. In both cases, the self-weight of models is included.
Linear static analyses using the method of finite elements were carried out (software SAP2000 v.9.0 [7]). The mechanical properties of masonry, common to all analyzed models are listed in Table 7.

Weight per unit volume	20,0	kN/m^3
Modulus of elasticity	2.000,0	MPa
Poisson's ratio	0,2	
Compressive strength	1,5	MPa
Tensile strength	0,1	MPa
Initial shear strength, under zero compressive stress	0,15	MPa

Table 7 Assumed mechanical properties of masonry

The results of the analyses are used to estimate values for the resistance parameters, "r_i". For this purpose all models are subjected to the same loading. The comparison between models is effectuated in terms of the magnitude and the distribution of principal stresses developed in those parts of the models that are critical for the resistance thereof. Those comparisons allow for values of factors "r_i" to be proposed. In what follows, some selected results of the parameter analyses are presented to highlight the calibration procedure that was adopted.

The Effect of the Percentage of Openings Along the Perimeter of the Building

In order to assess the effect of this parameter on the vulnerability of the structure, the eight models shown in Figure 1 were subjected to in-plane loading (10kN per m^2 of vertical area). The examined models of single free-standing walls (6m long and 3m high) cover various percentages of openings (from zero to 50%), as well as various arrangements for the same percentage of openings. The results have shown (Figure 2) that, for example, the maximum principal stresses in the middle region of the central pier are twice as high regarding the model with 50% openings compared to the respective stresses of the wall without openings. On the contrary, in case doors are arranged instead of windows in a model, the resulting principal stresses are not significantly affected.
It has to be noted that high stresses are typically observed in the corners of the openings. Nevertheless, those stresses are not taken into account for two reasons: (a) Typically, existing masonry buildings are characterized by better quality of masonry around openings (large dimension cut stones, small thickness mortar joints, etc.) and (b) The opening of cracks in the corners of the openings does not affect significantly the overall seismic behaviour of the building.

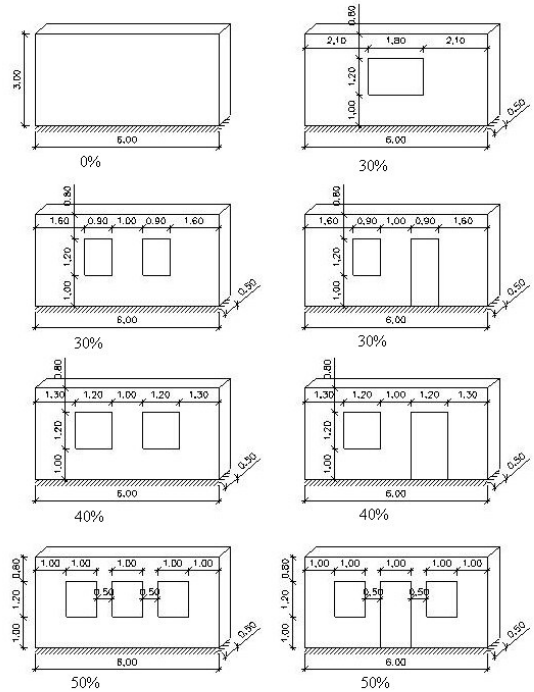


Figure 1 Models with different percentages of openings.

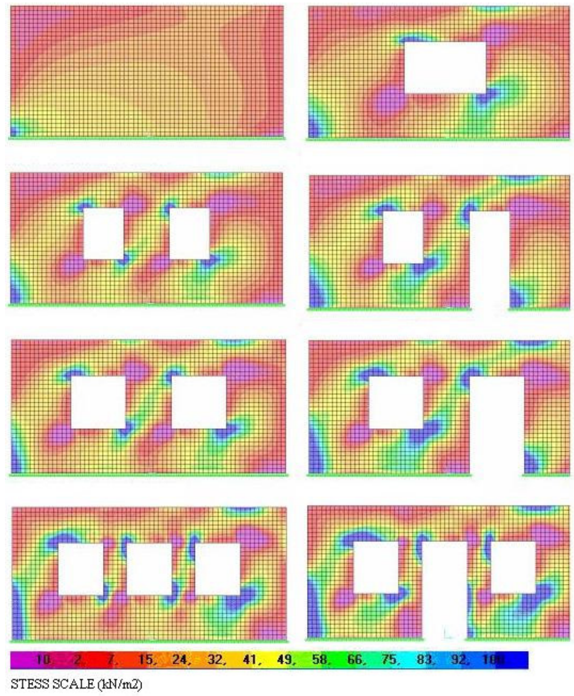


Figure 2 Maximum principal stresses for a horizontal, in plane load equal to 10kN/m^2

The same models of Figure 1 were subjected to the second load case as well (i.e. to different horizontal load value for each model that produce, however, the same magnitude of principal stresses. The load value, P, for each model is normalized to the load value, P_0, of the wall without openings. The values of P/P_0 ratio plotted against the percentage of openings (Figure 3) allow for the estimation of the effect of this parameter on the resistance of single walls loaded in-plane. Thus, adequate values for the factor r_2 are proposed.

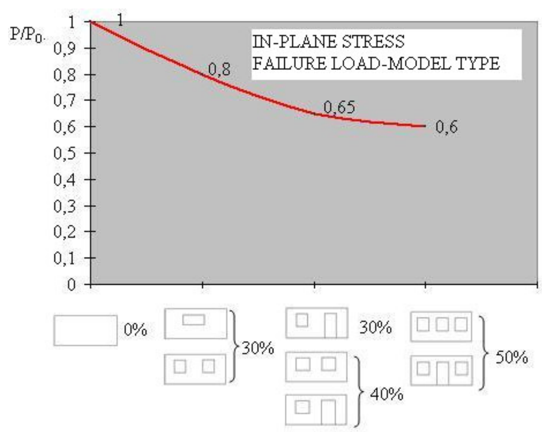


Figure 3. Relationship between the P/P_0 ratio and the percentage of openings, for in-plane loading of shear walls.

The Effect of the Number of Storeys

Following the procedure described for the previous parameter, analyses carried out on the models of Figure 4 have shown that the magnitude of the principal stresses in the central piers of the ground floor increases proportionally with the number of storeys.

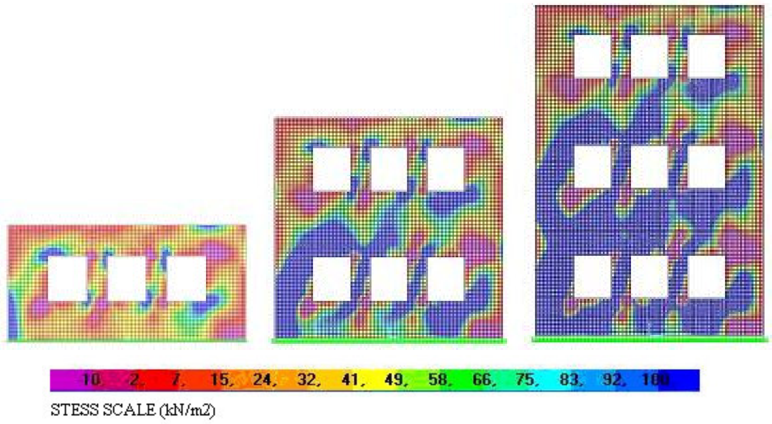


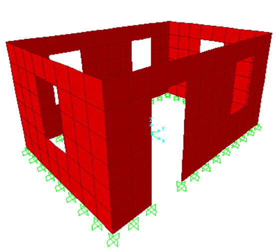
Figure 4 Maximum principal stresses of one-storey, two-storey and three-storey single wall subjected to in plane horizontal load of 10kN/m^2.

The Effect of Connection Between Longitudinal and Transverse Walls

In order to examine the effect of cooperation between longitudinal and transverse walls, eight models of free standing single-storey walls with intersecting walls at one or both vertical edges, with and without openings were considered. The models were subjected to in-plane loading. The performed analyses have shown that the principal stresses in a wall connected with transverse walls at both vertical edges are reduced by approximately 50%, compared to the respective stresses of an isolated wall of identical geometry.
Analyses carried out on similar models subjected to out-of-plane loading have proven the effect of the distance between transverse walls (i.e. the effect of the span of the out-of-plane loaded wall). For example, for the examined 3m high wall, the increase of its span from 4m to 8m led to increase of the out-of-plane bending moments by a factor of 2,0.

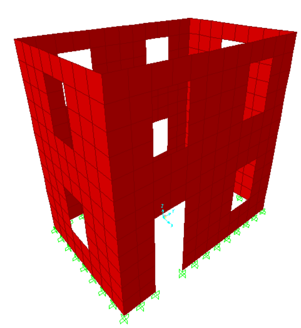
The Effect of Diaphragm Action at Floor and Roof Levels. The Effect of Tie-Beams

As the role of diaphragms and tie-beams is known to be of primordial importance for the seismic behaviour of masonry buildings, significant effort was devoted to the analytical investigation of this effect. For this purpose, two basic models of entire buildings (Figure 5) were subjected to parameter analyses (consisting of shell elements for stone masonry). Table 8 summarizes the cases that were analysed. Six loading cases were considered (with the seismic action along one or both main axes of the buildings) to account for the effect of the examined parameters on both in- and out-of-plane behaviour of the models.



(a)

Buildings dimensions:
L_x=4,0m
L_y=6,0m
H =3,0m and 6,0m
b_w=0,5m
Openings (windows) dimensions:
l=1,0m, h=1,5m
Percentage of openings: 30%
Lintel at: 2,5m and 5,5m



(b)

Figure 5 Geometry of the model-buildings: (a) one storey building (b) two storey building

Parameter analyses have confirmed the positive effect of rigid diaphragms at floor and/or roof levels on the resistance of the building. As an example, it is mentioned that, as shown in Figures 6 and 7, for both examined models, the presence of rigid diaphragms leads to a reduction of out-of-plane bending moments by approximately 80%. A similar role (less pronounced though) is identified for tie-beams. A summary of the results of this group of analyses is presented in Figures 6 and 7. The calculated bending moments refer to one of the walls that are perpendicular to the direction of the seismic action.

Model name	Description
IS	Basic one-storey model (figure 5 (a) (without tie-beams or diaphragms)
IS-1DZ	One-storey building with concrete tie-beams at floor level
IS-2DZ	One-storey building with concrete tie-beams at floor and lintel levels
IS-1DZJL	One-storey building with timber tie-beams at floor level
IS-2DZJL	One-storey building with timber tie-beams at floor and lintel levels
IS-PT	One-storey building with wooden frame floor, without tie-beams
IS-DF	One-storey building with a rigid diaphragm
OR	Two-storey building (figure 5(b)(without tie-beams or diaphragms)
OR-2DZJL	Two-storey building with timber tie-beams at floor levels
OR-PT	Two-storey building with wooden frame floors
OR-1DF	Two-storey building with a rigid diaphragm at roof level
OR-2DF	Two-storey building with two rigid diaphragms at intermediate floor and roof level

Table 8 Examined cases of building models

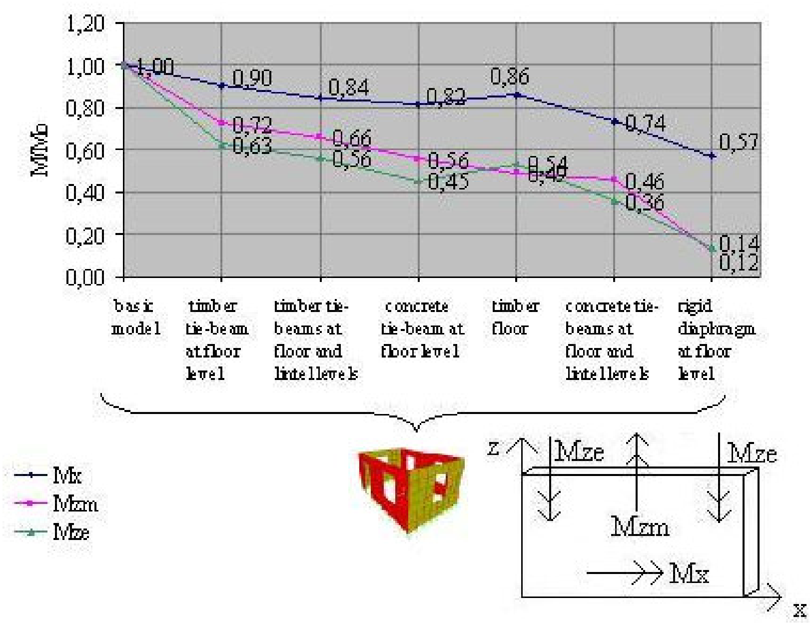


Figure 6 Seismic action along the smaller axis of the building: Bending moments Mx and Mz (M) normalized to the respective bending moments developed in the basic one-storey model (M_0).

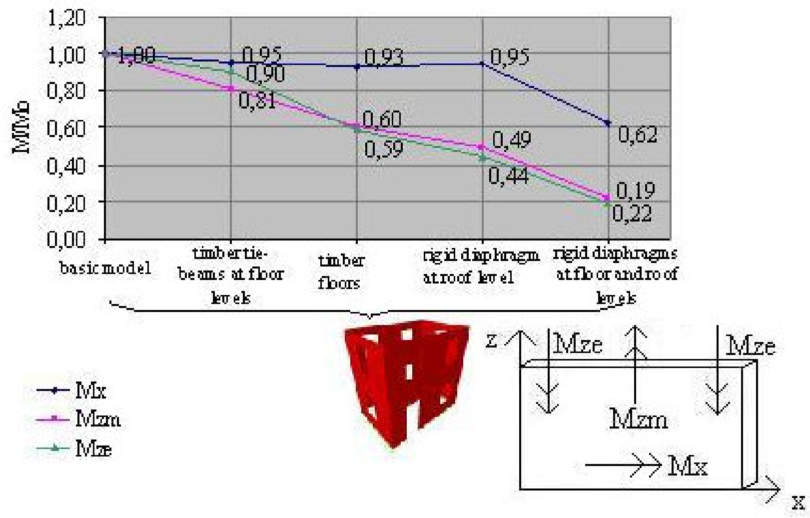


Figure 7 Moments Mx and Mz (M) normalized to the moments of the basic two-storey model for seismic action along the short dimension of the buildings (M_0).

EVALUATION OF THE PROCEDURE-CALIBRATION OF THE SCORING SYSTEM

As mentioned in the previous sections of this paper, parameter analyses were performed on individual elements, on subassemblages, as well as on simple model buildings. Such analyses may be valuable for the estimation of the effect of various structural parameters on the overall seismic behaviour of the buildings. Nevertheless, this type of analyses (a) does not provide information about the weighing factor of each influencing structural parameter and (b) does not allow for assessment of the entire methodology on which the proposed scoring system is based.

In order to check the efficiency of the scoring system and to evaluate the significance of each structural parameter, a further series of analyses was planned and is still in progress. Within this second part of the work, entire buildings very similar in geometry with those belonging to various historic systems are selected.

The proposed scoring system is applied to the buildings and their vulnerability index is calculated.

Subsequently, the buildings are analyzed for conventional seismic actions, according to the prescriptions of the current Aseismic Code. It should be noted that, at this step, the parameters related to hazard assessment are taken identical for the examined buildings, whereas the importance factor "A" is taken equal to 1,0. Thus, only parameters related to the resistance of the buildings are examined and assessed.

The results of those analyses are used to calculate the margins of safety of each element, of the connections thereof, as well as of the entire building. By changing various parameters (e.g. by modifying the percentage of openings or by adding a rigid diaphragm at roof level, etc.) and by re-calculating the margins of safety, one may judge about the weighing factor of each structural parameter.

It is evident that a large number of analyses are needed to reach the goal of calibration of the scoring system. Nevertheless, analyses carried up to now seem to indicate that the logic of the proposed scoring system is sound and that the effect of the examined parameters is realistically predicted by the rapid screening method.

CONCLUSIONS

A simple scoring system is developed with the purpose to provide qualitative assessment of the seismic vulnerability of masonry buildings.
The system takes into account basic structural characteristics of the buildings related both to the resistance of individual structural elements (e.g. the percentage of openings in a wall) and the joint action of structural elements (e.g. the connection of intersecting walls or the diaphragm action of floors and roof).
Resistance parameters are combined with seismic hazard parameters, as well as with the importance factor of each structure to form the vulnerability index.
Although the calibration of several resistance parameters through a systematic analytical work is still in progress, it seems that the logic of the system is sound and it may give indicative but realistic vulnerability indices. Those indices may allow to identify, within a group of structurally similar buildings, the most vulnerable ones.

REFERENCES

[1] Kapetana, P., Dritsos, S., "Seismic assessment of buildings by rapid visual screening procedures", *Sixth International Conference on Earthquake Resistant Engineering Structures, June 2007, Bologna, Italy, organized by Wessex Institute of Technology, UK.*
[2] FEMA (Federal Emergency Management Agency) 154 report, "Rapid Visual Screening of Buildings for Potential Seismic Hazards: a Handbook", *2002, Earthquake Hazards Reduction Series (EHRS) Publication, Federal Emergency Management Agency, P.O. Box 70274, Washington, D.C. 20024*
[3] FEMA (Federal Emergency Management Agency) 155 report, "Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation", *2002, Earthquake Hazards Reduction Series (EHRS) Publication, Federal Emergency Management Agency, P.O. Box 70274, Washington, D.C. 20024*
[4] Sinha, R., Goyal A., "A National Policy for Seismic Vulnerability Assessment of Buildings and Procedure for Rapid Visual Screening of Buildings for Potential Seismic Vulnerability" *Dept. of Civil Engineering, Indian Institute of Technology, Bombay. www.civil.iitb.ac.in/~rsinha/Vulnerability_Assessment.pdf*
[5] EAK 2000, Greek Earthquake Resistant Design Code, *Ministry of Environment, Planning and Public Works, Athens, 2000 [in Greek]*
[6] Patta, D., "Seismic evaluation of existing masonry buildings: calibration and proposals", MSc *Thesis, Postgraduate Program "Analysis and Design of Structures", National Technical University of Athens, 2006 [in Greek]*
[7] SAP 2000, Nonlinear Version 9, *Computers and Structures, Inc., University Avenue, Berkeley, CA 94704; 1995*