DAMAGE PROBABILITY MATRICES DERIVED FROM EARTHQUAKE STATISTICAL DATA

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ABSTRACT: A methodology is presented for the empirical vulnerability assessment of typical building types, representative of the building stock of Southern Europe, based on processing of a large set of statistical data. The observational database is obtained from post-earthquake surveys carried out after the 7-9-1999 Athens earthquake and comprises 180.945 damaged buildings. A damage scale is presented wherein the performance levels are defined according to the physical description of the seismic damage and, as well, in terms of structural and economical damage index. The seismic demand is described by estimating the macroseismic intensity for each region. The relative frequency of the different damage states, for each structural type and each intensity level, is computed, in terms of damage ratio by evaluating the ratio of the number of damaged buildings belonging to a specified structural type and a region with a certain intensity level, to the total number of buildings of the same region and building class. Following the pre-described methodology damage probability matrices (DPM) and vulnerability curves are obtained for specific structural types.

KEYWORDS: Seismic vulnerability, earthquake damage, DPM, vulnerability curves

1. INTRODUCTION

The empirical vulnerability assessment is based on the distribution of damage reported in post-earthquake surveys and treats these data according to statistical procedures. The observational source is the most realistic as it includes the real response of the exposed building stock and represents a physical experiment in scale 1:1. The difficulty focuses on the lack of a sufficiently large set of reliable empirical data, due to the limited number of damaging earthquakes, covering a wide range of ground motions [Eleftheriadou & Karabinis, 2008, Rossetto & Elnashai, 2003, Dolce et al., 2003]. The current research presents a methodology of the empirical seismic vulnerability assessment of typical building types, representative of the building stock of Southern Europe, based on processing of a large set of statistical data. The observational database is obtained from post-earthquake surveys carried out after the 7-9-1999 Athens earthquake and comprises 180.945 buildings which developed damage in several degree, type and extent. A process has been followed for the classification of selected building types representative of the materials, the seismic codes and the construction techniques used in Greece, and generally in Southern Europe, during the last century. A damage scale is presented wherein the performance levels are defined according to the physical description of the seismic damage and, as well, in terms of structural and economical damage index. The seismic demand is described by estimating the macroseismic intensity for each region from which the statistical data has been derived. For each building type the damaged buildings are distributed according to the degree of damage and the level of severity of the ground motion. In this way, the relative frequency of the different damage states, for each structural type and each intensity level, is computed, in terms of damage ratio by evaluating the ratio of the number of damaged buildings belonging to a specified structural type and a region with a certain intensity level, to the total number of buildings of the same region and building class. Following the pre-described methodology damage probability matrices (DPM) and vulnerability curves are obtained for specific structural types. The wide homogeneous database adds to the reliability of the collected information and reduces the scatter on the produced results [Eleftheriadou, 2008].

2. STATISTICAL DATA

The observational database derived from post-earthquake surveys carried out after the 7-9-1999 Athens earthquake [Mw=5.9]. The damage dataset is developed after the first or/and the second round of inspections, which have been conducted in several regions of Athens, based on instructions provided by Earthquake Planning and Protection Organization (EPPO) of Greece. The entire collected observational data came from different sources. Hence, the initial files of the statistical dataset needed to be filtered and unified in a total database wherein each in situ inspection is reported once. After this complex and time-consuming work and after eliminating duplicate reports, the unified total database is derived referring to the extended urban region of Attica. This dataset consists of **296.919** unique inspections with the inscriptions of the first or/and the second round of inspections and the files with the characterization of “collapse”. It is essential to clarify that the number of the pre-mentioned inscriptions refers to the number of autopsies and does not coincide with the number of buildings. A new process of the unified database has been followed, resulting that the 296.919 inspections are associated to **180.945** damaged buildings. It is noted that many of the 180.945 buildings were not fully described and hence the corresponding buildings have been disregarded from the process.

Information about the total number of buildings per structural type for the regions mentioned in the database is provided by the National Statistical Service of Greece according to the results of the 2000 statistical census. Comparing the total number of damaged buildings (180.945) to the total number of buildings in the affected area (753.078) it is concluded that the dataset addresses the 24,03% of the total local population of buildings, which is a wide statistical sample. The extent of damage can also be estimated from this information by making the reasonable assumption that in the concerning area, the damaged building stock has been thoroughly investigated and recorded and that almost all the non-surveyed buildings refer to nearly undamaged structures.

2.1. Structural Types

A classification system to characterize the earthquake-exposed building stock and describe its damage is a necessary step to develop vulnerability models in order to achieve a uniform interpretation of data and results. The vulnerability assessment requires the division of buildings into groups with similar seismic behaviour due to a probable earthquake [Eleftheriadou & Karabinis, 2008]. In the current research, apart from the characteristics that affect the seismic response of a structure, the proposed classification system is also dependent on the provided information collected from the post-earthquake surveys. Unfortunately, the existence or not of *pilotis* (ground levels without infill panels) or other irregularities, which may influence the development of earthquake damage, is not known. In the statistical database, the structural systems are divided into four groups (Table 1): **1)** Reinforced concrete buildings (RC) with moment resisting frames or frame-wall; **2)** Mixed buildings (MIX) with vertical bearing structure constituted by elements of both masonry and reinforced concrete; **3)** Masonry buildings (MAS) with vertical elements of masonry and horizontal elements of reinforced concrete, metal or wood and **4)** Other buildings (OTH), which typically include any buildings not belonging to the previous groups. The reinforced concrete structures are further classified based on the different seismic code periods at the time of their design: RC1: without a seismic code or during the period 1959-1985; RC2: during the period 1985-1995; and RC3 after 1995.

Table 1 Typical Structural Building Types

Structural Type		Design Seismic Code Period
Reinforced Concrete (RC)	RC1	1959-1985 or without Seismic Code
	RC2	1985-1995
	RC3	After 1995
Mixed (MIX)	MIX1	1959-1985 or without Seismic Code
	MIX2	1985-1995
	MIX3	After 1995
Masonry	MAS	
Other	OTH	

The mixed structures are further classified into MIX1, MIX2, and MIX3 using identical criteria. The threshold of each period is identified with a change in Greek seismic regulations. Buildings constructed before and after the introduction of the first Seismic Code are often treated similarly in Greece [National Technical Chamber of Greece, 2006].

2.1. Seismic Demand

In the current study, the seismic demand is described by estimating the macroseismic intensity I in the Modified Mercalli Scale (MMS) of each municipality mentioned in the database. The intensity values have been estimated based on the three following sources: **1.** the information provided by the Geodynamic Institute of the National Observatory of Athens (NOA) [Kalogeras & Stavrakakis, 2001], **2.** the results of a research programme referring to the estimated macroseismic intensities of the meizoseismal area [Gazetas et al., 2001] and **3.** the existing isoseismal intensity maps which display significant similarity between them [Protonotarios, 1999, Schenková et al., 2007, Hutchings et al., 2007].

The macroseismic intensity of each region is defined based on the pre-mentioned sources. The intensity values that are estimated in the 117 municipalities in the database vary from V to IX. The majority of the municipalities belong to weak intensity regions and only a few municipalities from the certain damage data are found in the area encircled by high intensity isoseismals. The assumption that each municipality has a certain level of seismic severity is necessary for the development of Damage Probability Matrices (DPMs). Moreover, the current research provides the advantage of satisfying the need of homogeneity in the presented large amount of damage data, all derived from the post-earthquake surveys of the same seismic event, covering a wide range of ground motions in several regions with similarities in the building stock and the soil conditions.

3. PROPOSED DAMAGE SCALE

A new damage scale is proposed for the reinforced concrete (RC) buildings wherein a calibration of seismic damage is presented beyond the qualitative description of the performance levels. The proposed scale is subdivided into seven damage levels, each of which is defined in terms of structural and non-structural damage, which would be expected in a future seismic scenario in the four main structural types of RC buildings that are met in Europe: ductile frames, non-ductile frames, frames with masonry walls and mixed buildings. Definition of performance levels in descriptive terms is not sufficient for the development of vulnerability curves. In order to consider the different damage rates of lateral-load systems and hence relate the curves to the building type, the scale must be calibrated to a measurable structural response parameter. In the proposed damage scale the performance levels, ranging from “none” damage to “collapse”, are defined according to the physical description of the seismic damage and, as well, in terms of structural and economic damage index. The different drift *thresholds*, which vary significantly for ductile and non-ductile systems, for the associated damage states of each structural type have been adopted by experimental data and theoretical analyses [Ghobarah, 2004, Foltz, 2004]. The economic damage index (in monetary loss) expresses the cost of repair as a fraction of the total cost of the building. The calibration of the earthquake damage by presenting both structural and economic damage index in the same scale, allows their direct comparison and correlation. The proposed calibration for the different levels of seismic damage severity regarding the economic damage index is in accordance with the familiar manner of damage classification in Greece [National Technical Chamber of Greece, 2006]. It must be noted that the proposed methodology regarding the post-earthquake surveys and the pre-defined limits of damage severity expressed in monetary losses, is similar to the instructions provided by EPPO and FEMA.

The description of damage in every performance level is based on familiar existing damage scales [Fema 273, 1997, Rosetto & Elnashai, 2003, Karabinis & Eleftheriadou, 2006, 2007 & 2008]. The use of the new scale does not call for specialized knowledge, whereas intentionally it does not differ substantially from the familiar to many engineers, manner of estimation of post-earthquake damage. The novelty of the new scale is that it

Table 2 Proposed Damage Scale

PROPOSED DAMAGE SCALE				TYPICAL STRUCTURAL TYPES OF RC BUILDINGS							
				DUCTILE MRF		NON-DUCTILE MRF		INFILLED MRF		MIXED	
ECONOMIC DAMAGE INDEX	DAMAGE LEVEL	GREECE	FEMA	ECONOMIC DAMAGE INDEX	DESCRIPTION	ECONOMIC DAMAGE INDEX	DESCRIPTION	ECONOMIC DAMAGE INDEX	DESCRIPTION	ECONOMIC DAMAGE INDEX	DESCRIPTION
0%	None	None	None	0.0%	None	0.0%	None	0.00%	None	0.00%	None
0-1%	Slight	Green	Operational	<0.20%	Minor cracking in partitions, infills and ceilings, hairline craks of structural elements	<0.10%	Minor cracking in partitions, infills and ceilings, hairline craks of structural elements	<0.10%	Minor cracking in partitions, infills and ceilings, hairline craks of structural elements	<0.20%	Minor cracking in partitions, infills and ceilings, hairline craks of structural elements
1-10%	Light	Yellow	Immediate Occupancy	0.4%	Minor cracks in structural elements, facades and partitions, hairline cracking in beams/columns near joints (<1mm)	0.2%	Minor cracks in structural elements, facades and partitions, hairline cracking in beams/columns near joints (<1mm)	0.20%	Cracks at wall-frame interfaces, diagonal cracking of walls, limited crushing of bricks at beam/column connections, start cracking at corners of openings	0.40%	Hairline cracking on shear-walls and coupling beams, onset of concrete spalling
10-30%	Moderate		Life Safety	<1.00%	Cracks in most beams and columns with larger flexural cracks, yielding in a limited number of stuctural elements, start of concrete spalling	<0.50%	Flexural and shear cracks in most beams and columns, yielding in a limited number of stuctural elements, limited shear cracking and concrete spalling	<0.40%	Increased brick crushing at beam-column connections, start of structural damage, some diagonal shear cracking in structural elements mostly of the exterior frames	<0.90%	Cracks in most shear walls, some walls reach yield capacity, increased diagonal cracking and concrete spalling at wall corners and around openings, extensive cracks in coupling beams
30-60%	Extensive	Red	Collapse Prevention	>1.00%	Some structural elements have reached ultimate capacity, extensive flexural cracking, concrete spalling, bar buckling, short column failure, severe joint damage, permanent drift	>0.50%	Bar pull-out, loss of bond at lap-splices, broken ties, possible bar buckling and shear failure of structural elements, permanent drift	>0.40%	Extensive cracking of infills, falling bricks, partial failure of many infills, out-of-plane bulging, heavier damage in frame members, some shear failure, permanent drift	>0.90%	Most shear walls have exceeded yield and some walls reach ultimate capacity, boundary element distress, bar buckling, extensive through-wall cracks, shear failure of some frame members, sliding at joints
60-100%	Partial Collapse			1.8%	Collapse of a few columns, a building wing or single upper floor	0.8%	Shear failure of many columns or impending soft-storey failure	0.70%	Shear failure of beams and/or columns causing partial collapse, near total infill failure	1.65%	Coupling beams-panels shattered and virtually disintegrated, some shear walls fail
100%	Collapse	Black	Collapse	>3.00%	Complete or impending building collapse	>1.00%	Complete or soft-storey failure at ground floor	>0.80%	Complete or impending building collapse	>2.75%	Complete or impending building collapse

imports the measurable calibration of damage, in terms of structural and economic damage index, which depends on severity and the extent of damage, right from the field where autopsy is conducted.

4. DAMAGE PROBABILITY MATRICES

In the current study Damage Probability Matrices (DPMs) are produced and vulnerability curves are obtained in the sequence, based on these matrices. The present process provides the advantage of satisfying the need of homogeneity in the presented large amount of damage data, all derived after the occurrence of the same large magnitude seismic event (7-9-1999) in an extended urban region, covering a wide range of ground motions in several regions with similarities in the building stock and the soil conditions.

After the estimation of the macroseismic intensity, five groups of intensity levels from V to IX are formed including the 117 municipalities of the statistical data. For the development of DPMs the buildings of the damage data needed to be classified into structural types. The chosen structural types are identical to those proposed by the National Statistical Service of Greece. In the sequence, the classified buildings into structural types are subdivided according to the intensity level. The next step is to develop DPMs for each building type based on the distribution of damage for the levels of severity of the seismic input.

The assumption, which inevitably has been made, by characterizing each municipality with a unique intensity value is justified as there are similar construction practices and soil conditions and mainly because the total number of the buildings, in each region, can be determined. Hence, for each municipality, the number of surveyed buildings belonging to a certain structural type is compared to the total number of buildings of the same structural type provided by the General Secretariat of National Statistical Service of Greece. In addition, for each building type and for each intensity level, the relative frequency of the different damage states has been computed in terms of damage ratio. The latter is evaluated as the ratio of the number of damaged buildings belonging to a specified structural type and a region with a certain intensity level, to the total number of buildings of the same region and building class, obtaining a damage probability matrix (DPM). The produced DPMs were derived from the real data of 73468 buildings. As it has been already mentioned among the 180.945 buildings there were many which were not fully described. Hence, the corresponding buildings have been disregarded from the process. In the same way, for the development of the DPMs it was used the total number of buildings of the regions from which derived the buildings that were classified into structural types (namely 73.468 buildings out of the total number of 710.556 buildings) and not the total number of buildings of the database (namely 180.945 buildings out of the total number of 753.078 buildings).

The information from the database that is used in this paper refers only to qualitative characterizations of damage level, based on instructions provided by EPPO [1997 & 1984], in order to define whether its seismic capacity is adequate against future expected seismic forces, as follows: a) Green: building with no or light damage, or building whose earthquake resistance has not been reduced, b) Yellow: building with moderate damage and reduced earthquake resistance, c) Red: building with very heavy damage or partial collapse, and d) Collapse: building that has collapsed or is under demolition. In the collected data, there was no information about the cost of repairs or the description of damage. The vulnerability models proposed by the National Technical Chamber of Greece-NTCG [2001 & 2006] were mostly based on a hybrid methodology involving elements from both empirically and analytically calculated structural damage indices which have been correlated to monetary loss [Kappos et al., 2002; ITSAK-AUTH, 2004]. The need of calibration of the qualitative description of damage is satisfied by the use of the measurable economic damage index presented in the proposed damage scale in Table 2.

Five damage states were defined: **1.** No damage (DS0), **2.** Slight damage – Green (DS1), **3.** Light-Moderate damage – Yellow (DS2), **4.** Extensive damage-Partial Collapse – Red (DS3), **5.** Collapse – Black (DS4). The range of damage index in monetary loss for the corresponding five damage states is: 0% (DS0), 0-1% (DS1), 1-30% (DS2), 30-100% (DS3) and 100% (DS4). The Central Damage Factor (CDF) for each damage state is presented in Table 3. During the development of damage relationships, it has been assumed that half of the undamaged buildings have a CDF equal to 0.125 and the others equal to 0.50. This assumption has been shown to lead to better results [ITSAK-AUTH, 2004]. The 'thresholds' of the damage states are in accordance with those proposed by the NTCG [2001 & 2006] and FEMA. Moreover, the damage states are connected with the physical description of damage noticed in the four main structural types of RC buildings presented in the proposed damage scale.

Table 3 Damage States

Damage State		Definition	Central Damage Factor
None	DS0	No damage	$0.125*N^{(1)}/2+0.50*N^{(1)}/2$
Green	DS1	Slight damage	0.50
Yellow	DS2	Light-Moderate damage	15
Red	DS3	Extensive damage-Partial Collapse	65
Black	DS4	Collapse	100

(1) Where N is the percentage of the buildings with nearly no damage (nearly undamaged).

For each building type and for each intensity level, the relative frequency of the different damage states has been computed in terms of damage ratio obtaining a DPM [Eleftheriadou, 2008]. In the Tables 4 to 8 the produced DPMs are presented concerning the pre-described structural types, which were derived from the statistical dataset. Observing the development of damage, it is seen that the buildings which belong to RC or MIX structural types presented similar seismic behaviour and hence the structural types of RC1 and MIX1, RC2 and MIX2, RC3 and MIX3 have been unified [Karabinis & Eleftheriadou, 2007]. In addition, there is no discrimination between the RC and Mixed buildings in the structural types provided by the National Statistical Service of Greece. For each level of ground motion severity, the percentage of the damaged buildings used in the development of DPMs to the total population of buildings to estimate the statistic reliability has been also evaluated. Based on literature review [Kappos et al., 2002] it has been concluded that a statistical sample representing almost 10% of the entire building stock is considered quite representative of the whole. As it can be noticed in the produced DPMs, this level of representation is satisfied for several intensity levels. As a result, the evaluated median damage factors (MDF) of these levels are the most reliable.

Table 4 DPM for the RC1-MIX1 Structural Type

RC1-MIX1							
Damage State		**Central Damage Factor (%)**	**Intensity Level MMS (I)**				
			V	**VI**	**VII**	**VIII**	**IX**
None	DS0	0.125*N(1)/2+0.50*N(1)/2	97.93	95.03	85.52	69.83	43.96
Green	DS1	0.50	0.66	1.68	4.96	9.16	9.20
Yellow	DS2	15	1.33	3.08	9.08	19.65	41.21
Red	DS3	65	0.07	0.18	0.27	0.81	3.97
Black	DS4	100	0.01	0.03	0.17	0.55	1.66
Median Damage Factor (MDF)			**0.56**	**0.92**	**2.00**	**4.28**	**10.61**
% of the data to the total population			2.07	4.97	14.48	30.17	56.04

(1) Where N is the percentage of the buildings with nearly no damage (4.886 to 165.665 buildings).

Table 5 DPM for the RC2-MIX2 Structural Type

RC2-MIX2							
Damage State		**Central Damage Factor (%)**	**Intensity Level MMS (I)**				
			V	**VI**	**VII**	**VIII**	**IX**
None	DS0	0.125*N(1)/2+0.50*N(1)/2	99.52	98.35	93.42	84.04	68.67
Green	DS1	0.50	0.20	0.73	2.81	6.77	7.13
Yellow	DS2	15	0.27	0.89	3.11	8.77	22.55
Red	DS3	65	0.01	0.02	0.58	0.28	1.15
Black	DS4	100	0.00	0.01	0.08	0.14	0.50
Median Damage Factor (MDF)			**0.36**	**0.46**	**1.23**	**1.94**	**4.88**
% of the data to the total population			0.48	1.65	6.58	15.96	31.34

(1) Where N is the percentage of the buildings with nearly no damage (4.764 to 165.665 buildings).

Table 6 DPM for the RC3-MIX3 Structural Type

RC3-MIX3							
Damage State		**Central Damage Factor (%)**	**Intensity Level MMS (I)**				
			V	**VI**	**VII**	**VIII**	**IX**
None	DS0	0.125*N(1)/2+0.50*N(1)/2	99.69	99.35	96.53	88.61	70.58
Green	DS1	0.50	0.19	0.40	1.78	5.51	8.35
Yellow	DS2	15	0.10	0.22	1.63	5.61	19.59
Red	DS3	65	0.02	0.03	0.05	0.07	1.13
Black	DS4	100	0.00	0.00	0.01	0.20	0.35
Median Damage Factor (MDF)			**0.34**	**0.37**	**0.60**	**1.39**	**4.29**
% of the data to the total population			0.31	0.65	3.47	11.39	29.42

(1) Where N is the percentage of the buildings with nearly no damage (1.996 to 13.040 buildings).

Table 7 DPM for the MAS Structural Type

MAS							
Damage State		**Central Damage Factor (%)**	**Intensity Level MMS (I)**				
			V	**VI**	**VII**	**VIII**	**IX**
None	DS0	0.125*N(1)/2+0.50*N(1)/2	97.78	92.49	71.49	56.05	69.20
Green	DS1	0.50	0.54	1.53	5.72	10.39	5.43
Yellow	DS2	15	1.54	5.28	19.92	28.60	20.78
Red	DS3	65	0.13	0.62	1.83	2.65	3.67
Black	DS4	100	0.01	0.08	1.04	2.31	0.92
Median Damage Factor (MDF)			**0.64**	**1.57**	**5.47**	**8.55**	**(6.67)**
% of the data to the total population			2.22	7.51	28.51	43.95	30.80

(1) Where N is the percentage of the buildings with nearly no damage (2.260 to 56.182 buildings).

Table 8 DPM for the OTH Structural Type

OTH							
Damage State		**Central Damage Factor (%)**	**Intensity Level MMS (I)**				
			V	**VI**	**VII**	**VIII**	**IX**
None	DS0	0.125*N(1)/2+0.50*N(1)/2	98.35	94.94	86.12	77.17	72.97
Green	DS1	0.50	0.14	0.65	1.56	2.43	3.71
Yellow	DS2	15	1.14	3.65	8.93	13.17	12.76
Red	DS3	65	0.34	0.58	2.33	4.29	7.68
Black	DS4	100	0.03	0.18	1.06	2.94	2.88
Median Damage Factor (MDF)			**0.73**	**1.41**	**4.19**	**7.96**	**10.04**
% of the data to the total population			1.65	5.06	13.88	22.83	27.03

(1) Where N is the percentage of the buildings with nearly no damage (1.653 to 21.114 buildings).

It must be pointed out that the produced DPMs were derived from the real data of 73.468 buildings, which were subdivided according to the structural types, the damage characterization and the seismic input. However, in the specific statistical sample, 180.427 buildings had the characterisation of damage. Furthermore, the assumption that the buildings which are not classified in structural types belong to the undamaged structures, combined with the fact that the non surveyed buildings are considered undamaged, leads to underestimation of the probability of damage. In order to solve this problem, a second procedure was followed in order to include the remaining buildings, which were not classified in the structural types used here. For each municipality (with a certain intensity level), the ratio of the categorized buildings in structural types and damage levels to the total number of buildings with the same characterization of damage was calculated. Given the similar construction practices and soil conditions of each region, the assumption that the buildings are contributed in structural types according to the calculated ratio is justified. Following this procedure, new *proportional* DPMs were produced, including the proportioned number of 178.578 buildings. This was achieved by extending the same proportions of the damage distribution associated with the 73.468 buildings, into the 178.578 buildings. In addition, in both DPMs, the elimination of the buildings belonging to a structural type and having any degree of damage from the total number of buildings, lead to those buildings which have slight damage. A comparative investigation is fulfilled for the two types, *real* and *proportional* DPMs, concluding that their results are similar only with a slight increase in the values of the *proportional* DPMs due to the increase of the statistical data.

5. VULNERABILITY CURVES

Finally, vulnerability curves concerning specific structural types are obtained by correlating the values of the median damage factors of the *real* DPMS with the levels of severity of the seismic input. The vulnerability curves are presented in Figure 1. Intensities (I) and PGA's are correlated using the following empirical relationship for the area studied (Eqn. 5.1):

$$\ln(PGA) = 0.74 * I + 0.03 \qquad (1)$$

This is a recently proposed relationship, which was derived from the statistical processing of a large number of strong ground motions in Greece [Koliopoulos et al., 1998; ITSAK-AUTH, 2004]. This relationship has been calibrated for intensities up to IX, therefore, its validity for stronger macroseismic intensities is limited. The correlation between I and PGA would serve a posterior comparison between the vulnerability functions derived from this study and those that are proposed by EPPO [NTCG, 2001 and 2006]. In the EPPO vulnerability models, the parameter that characterizes the seismic input has been the ratio a_g/a_o, where a_g is the evaluated from the macroseismic intensity PGA and a_o is the unique value that characterizes each municipality in the Greek hazard map. For the buildings that belong in regions, that the design-date seismic zone identification differs from today's seismic zone, a relative coefficient is used in order to account for the change in the foreseen PGA's.

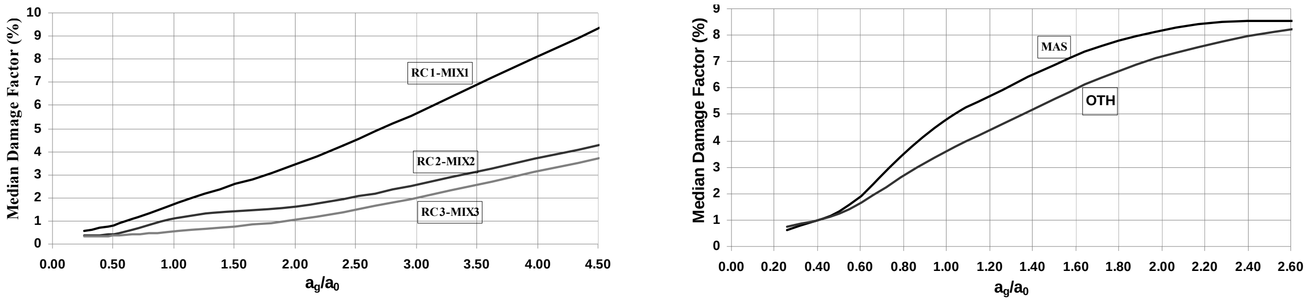

Figure 1 Vulnerability curves

6. DISCUSSION OF RESULTS AND CONCLUSIONS

A methodology is presented for the empirical evaluation of seismic vulnerability of typical building types based on processing of a large set of statistical data. The observational database is obtained from post-earthquake surveys carried out after the 7-9-1999 Athens earthquake and comprises 180.945 buildings which developed damage in several degree, type and extent. A process has been followed for the classification of selected building types representative of the materials, the seismic codes and the construction techniques used in Greece, and generally in Southern Europe, during the last century. The chosen structural types are also identical to those proposed by the National Statistical Service of Greece for the classification of buildings. A damage scale is presented wherein the performance levels are defined according to the physical description of the seismic damage and, as well, in terms of structural and economical damage index. The calibration of the earthquake damage by presenting both structural and economic damage index in the same scale, allows their direct comparison and correlation. The seismic demand is described by estimating the macroseismic intensity for each region from which the statistical data has been derived. For each building type the damaged buildings are distributed according to the degree of damage and the level of severity of the ground motion. Thus, the relative frequency of the different damage states, for each structural type and each intensity level, is computed, in terms of damage ratio by evaluating the ratio of the number of damaged buildings belonging to a specified structural type and a region with a certain intensity level, to the total number of buildings of the same region and building class. Following the pre-described methodology damage probability matrices (DPM) and vulnerability curves are obtained for specific structural types.

Important conclusions are drawn on the correlation analysis of the probability of damage as a function of the structural types and the period of construction. In general, buildings belonging to RC and MIX structural types presented an overall better seismic performance in the referring earthquake compared to masonry buildings. Furthermore, the buildings that are constructed according to older seismic codes developed heavier damage, in comparison with those designed with contemporary regulations, since the former are non-conforming to modern seismic detailing requirements and philosophy. This last conclusion confirms in practice the reliability of the contemporary seismic regulations and reveals their disparity to old seismic codes. This is a significant problem when one considers that the majority of the existing buildings are constructed using older regulations. The need for earthquake mitigation becomes urgent.

The empirical evaluation of seismic vulnerability relationships obtained in this study (Tables 4 to 8), allow their practical use in seismic risk analysis and scenarios. It should be mentioned that they do not essentially differ from the existing DPMs [NTCG, 2001 & 2006], especially when the most numerous intensity levels are examined, although the structural types are not exactly the same. Despite the fact that the DPMs refer to wide structural types, they depend on important, for the seismic response, parameters. The main differences in buildings classification are related to the height, the existence of pilotis and the discrimination between RC moment resisting frames (MRF) and mixed buildings (MRF with shear walls). Between the above mentioned characteristics the most important is the information about the existence of ground levels without infill panels. The parameter of height has been ignored in the recently developed vulnerability models [NTCG, 2006] whereas the information about MRF or mixed buildings is not available in the structural types proposed by the National Statistical Service of Greece.

It should be mentioned that the recently proposed DPMs [NTCG, 2006] have been modified comparing them to those that they were initially proposed [NTCG, 2001]. After conducting a comparison analysis it is concluded that: **1.** the DPM for the RC1-MIX1 structural type is similar to the referring in “Table 4.2” DPM [NTCG, 2006], **2.** the DPM for the RC2-MIX2 is more similar to the referring in “Table 4.5” and “Table 4.6” DPMs (and less similar to the DPMs of “Table 4.7” and “Table 4.8” in IX intensity level) and **3.** the DPM for the RC3-MIX3 is similar to the referring in “Table 5.32”, “Table 5.38” and “Table 5.44” DPMs [ITSAK-AUTH, 2004]. These conclusions verify in practice the proposed methodology of the empirical vulnerability assessment. However, the produced in this study DPMs have the advantage of being the most realistic as they include the actual response of the exposed building stock and they have been derived from a physical experiment in scale 1:1. Some differences are noticed comparing the produced DPM for masonry buildings to the corresponding existing matrices which they are possibly owed to the unreliable statistical sample in high intensity levels (a larger number of buildings in VII level and few buildings in IX). It is also important to stress that the derived vulnerability relationships do not intend to represent the structural performance of a single building. Nevertheless, it is believed that they represent, in a reliable way, the mean values of the prediction of damage distribution for selected typical classes of buildings in Greece and in Southern Europe. It is also concluded that the wide homogeneous database adds to the reliability of the collected information and reduces the scatter on the produced results.

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