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Evaluation of damage probability matrices from observational seismic damage data

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Abstract. The current research focuses on the seismic vulnerability assessment of typical Southern Europe buildings, based on processing of a large set of observational damage data. The presented study constitutes a sequel of a previous research. The damage statistics have been enriched and a wider damage database (178578 buildings) is created compared to the one of the first presented paper (73468 buildings) with Damage Probability Matrices (DPMs) after the elaboration of the results from post-earthquake surveys carried out in the area struck by the 7-9-1999 near field Athens earthquake. The dataset comprises buildings which developed damage in several degree, type and extent. Two different parameters are estimated for the description of the seismic demand. After the classification of damaged buildings into structural types they are further categorized according to the level of damage and macroseismic intensity. The relative and the cumulative frequencies of the different damage states, for each structural type and each intensity level, are computed and presented, in terms of damage ratio. Damage Probability Matrices (DPMs) are obtained for typical structural types and they are compared to existing matrices derived from regions with similar building stock and soil conditions. A procedure is presented for the classification of those buildings which initially could not be discriminated into structural types due to restricted information and hence they had been disregarded. New proportional DPMs are developed and a correlation analysis is fulfilled with the existing vulnerability relations.

Keywords: seismic vulnerability; damage probability matrices (DPMs); vulnerability curves; post-earthquake surveys

1. Introduction

Mankind witnessed the destructive results of strong earthquakes during the last decades in areas with densely concentrated population and buildings. The socio – economic and political impacts of seismic events to these environments, which are highly exposed to human and economical losses, mobilized committees and governments in the improvement of earthquake management by financing numerous projects for this purpose. However, earthquake damage estimation and risk management is still a developing research field. Pre- and post- earthquake upgrading of a city's existing building stock is one of the most conflictual and difficult types of public policy decisions.

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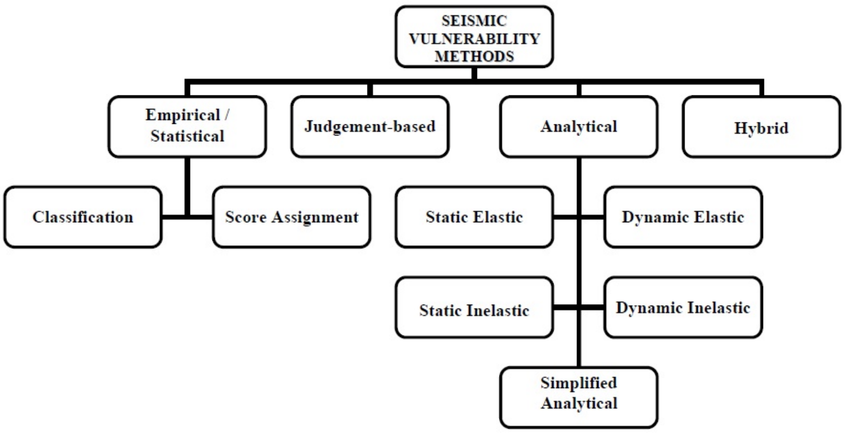

Fig. 1 Seismic vulnerability methods

Earthquake loss estimation methodologies rely on relationships between building performance and ground motion. Seismic vulnerability relationships attempt to predict for several building classes the degree and the extent of damage and estimate the probabilities reaching or exceeding various limit states at given levels of seismic demand severity. The devastating impacts of recent earthquakes have resulted in an increased awareness amongst populations, institutions, and governments, of the potential seismic hazard and the building's stock vulnerability to it (Glaister *et al.* 2002). Many seismic risk assessments (D' Ayala *et al.* 1997, Faccioli *et al.* 1999, Kappos *et al.* 1998, 2002, Dolce *et al.* 2003, 2006, Pitilakis *et al.* 2011) and vulnerability studies (Rossetto *et al.* 2003, Rota *et al.* 2006, National Technical Champer of Greece - NTCG 2006, Lagomarsino *et al.* 2006, Karabinis *et al.* 2007, Eleftheriadou *et al.* 2008a, 2008b, 2012, Eleftheriadou 2009) have been carried out as their results could turn out important decision - making tools for the reliable mitigation of losses and seismic risk management, allowing disaster plans to be drawn up.

The seismic vulnerability of a structure can be described as its susceptibility to damage by ground shaking of a given intensity. The aim of a vulnerability assessment is to obtain the probability of a given level of damage to a given building type due to a scenario earthquake (Calvi *et al.* 2006). The methods of vulnerability assessment can be generally classified into four groups depending on the sources of the provided damage information, as it is shown in Fig. 1. The empirical method for the vulnerability assessment, which has been applied in the present paper, is based on the distribution of recorded damage reported in post - earthquake surveys and generally treats these data according to statistical procedures (Yamaguchi *et al.* 2000, Yamazaki *et al.* 2000, Rossetto *et al.* 2003, Sarabandi *et al.* 2003, Rota *et al.* 2006, Eleftheriadou 2009, Eleftheriadou *et al.* 2011). Survey data can rarely provide a complete set of data mainly due to the limited number of damaging earthquakes and to the high number of structural types that are found in a building stock (Dolce *et al.* 2003). However, the observational source, in case that it is available, is the most realistic and represents a physical experiment in scale 1:1. It includes the real response of the exposed building stock, taking into account all the structural characteristics, topography, site, soil-structure interaction and the ground motion. 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 (Rossetto *et al.* 2003, Rota *et al.* 2006, Lagomarsino *et al.* 2006, Karabinis *et al.* 2007, Eleftheriadou 2009, Eleftheriadou *et al.* 2008a, 2008b, 2011). Judgement - based method relies on the statistical treatment of the knowledge provided by a team of experts and it depends on the subjective experience (ATC-13 1985, Lang 2002, Giovinazzi 2005). In score assignment method potential structural deficiencies are identified from observed correlations between damage and structural characteristics in order to estimate seismic vulnerability (ATC-13 1985, FEMA-178 1992, FEMA-154 1998, FEMA-310 1998, Cherubini *et al.* 1999, Lang 2002, Karabinis 2003, Giovinazzi 2005, Kappos *et al.* 2006, Yakut *et al*. 2006). It is usually applied in the first phase of the estimated damage in vulnerable buildings which may afterwards be analyzed in more detail for applying upgrading strategies. Analytical methods adopt damage distributions from statistical treatment of the results of analysis of structural models under increasing earthquake loads. Their reliability depends on the modelling capabilities and the number of assumptions that are necessary to model a real structure as a computational model and only a limited number of structures can be analyzed for practical reasons. A simplified analytical method, which constitutes a sub - method of analytical, estimates the seismic behaviour of building models by using simple mechanic parameters or mechanisms (D' Ayala 2005, D' Ayala *et al.* 1997, 2002, Spence *et al.* 1999, Calvi 1999, Pagnini *et al.* 2011). In the analytical vulnerability assessment with the application of linear static elastic procedure the building is modelled as an equivalent single - degree of freedom (SDOF) system with a linear elastic stiffness and an equivalent viscous damping (Wen *et al.* 2002). Static elastic method is commonly used for design purposes and it is not demanding in its application regarding cost, time and building's modelling. However, its applicability is restricted to regular buildings for which the first mode of vibration is predominant. In the static inelastic procedure the nonlinear force - deformation characteristics of individual components and elements due to nonlinear material response is taking into account. Therefore, the calculated internal forces and deformations, are taking into account will be more reasonable approximations of those expected during an earthquake. However, only the first mode of vibration is considered and hence these methods are not suitable for irregular buildings for which higher modes become important (ATC-40 1996, FEMA-273 & 274 1997, FEMA-356 2000, Kishi *et al.* 2000). Furthermore, in the static dynamic method the building is modelled as a multi – degree – of - freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix. Higher modes are considered and the method is suitable for irregular buildings. The seismic input is modelled using either modal spectral analysis or time history analysis and the internal forces and displacements are estimated through the linear elastic analysis including the disadvantages of the linear approach. In addition, in dynamic inelastic method the building model, similarly to the nonlinear static procedure, takes into account the inelastic material response often using finite elements. Several time - history analysis are required applying different ground motion records in order evaluate time – step – by – time - step the building response. Important results have arisen from the use of the nonlinear dynamic procedures (Singhal and Kiremidjian 1996a, 1996b, Calvi 1999, Chrysanthopoulos *et al.* 2000, Vamvatsikos and Cornell 2002, Glaister and Pinho 2002, Jalayer and Cornell 2003, Uma *et al.* 2006). Finally, hybrid methods typically involve the combination of analytical or judgement - based data with observational or experimental data, although the additional sources of the latter are often limited in quantity, thus mitigating the scarcity of observational data, the subjectivity of judgemental data and the modelling deficiencies of analytical procedures (Singhal and Kiremidjian 1998, Dolce *et al.* 2003, 2006, Kappos *et al.* 1998, 2010, Elnashai 2006).

The current research has the advantage of satisfying the need of the pre - mentioned homogeneity in the presented large amount of damage data derived from Athens post - earthquake surveys after the occurrence of a large magnitude near field seismic event (7-9-1999) in an extended densely populated urban region. The study constitutes a sequel of a previous research (Eleftheriadou *et al.* 2011). The produced DPMs in the pre - mentioned paper were derived from the available actual data of 73468, derived from a created damage database with totally 180945 buildings, which were able to be subdivided according to structural type, damage characterization and seismic input. The rest of the damaged buildings were not fully described and hence the corresponding buildings had been disregarded from the referring process. However, in the created damage database for 180427 buildings the characterization of damage was available. The assumption that the buildings which are not classified in structural types belong to 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 supplementary procedure is presented here in order to include the remaining buildings, which were not initially classified into structural types. A wider damage database (178578 buildings) is developed compared to the Damage Probability Matrices (DPMs) of the first presented paper (73468 buildings) after the elaboration of the results from post - earthquake surveys.

The dataset comprises buildings which developed damage in several degree, type and extent. The research focuses on the empirical seismic vulnerability assessment of typical building types, representative of the materials, the seismic codes and the construction techniques used in Greece, and generally in Southern Europe, based on processing of a large set of observational data. The total number of buildings, corresponding to the predetermined building types of each region, is provided by the National Statistics Agency of Greece. Two different parameters are estimated for the description of the seismic demand. For each building type the damaged buildings are distributed according to the degree of damage and the level of severity of the ground motion. The relative and the cumulative frequencies of the different damage states, for each structural type and each intensity level, are computed and presented, in terms of damage ratio. A procedure is presented for the classification of the buildings with restricted information which initially had been disregarded and new *proportional* Damage Probability Matrices (DPMs) are developed for typical structural types. A correlation analysis is fulfilled between the produced *proportional* and the existing vulnerability models in areas with similar soil conditions and construction practices.

2. Development of the damage database

The observational database of post-earthquake surveys carried out after the 7th of September 1999 near field moderate – to - strong (Mw=5.9) Athens earthquake (Eleftheriadou *et al.* 2012). The observational database is developed after the first or/and the second round (or level) 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 first round of inspection is a rapid visual screening method conducted by a couple team of engineers in order to define in a short period of time the seismic safety of numerous structures. A second and more detailed level of inspection is followed for those buildings with inadequate estimated seismic performance in order to prioritize them for further more detailed analytical assessment that it would be required to design a rehabilitation scheme. The entire collected observational data came from different sources ((Post-Earthquake Crisis Management Division of Axarnes region (including the regions of Filadelfeia – Axarnes – Ano Liosia) and of Piraeus region (including the regions of Piraeus – down town of Athens – Peristeri – Eleusina), National Service for the

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	

Rehabilitation of Earthquake Victims)) and raised the enormous number of 535152 reports of post - earthquake surveys. The initial files of the damage dataset needed to be filtered and unified in a total database wherein each in situ inspection is reported once. After eliminating duplicate reports, the unified total database consisted of 296919 unique inspections referring to the extended urban region of Attica with the inscriptions of the first or/and the second round of inspections and the files with the characterization of "collapse". However, the number of the pre - mentioned inscriptions refers to the number of autopsies and does not coincide with the number of buildings. A new elaboration of the unified database has been followed (checking the first and the second round of inspections), driving to the conclusion that the 296919 inspections are associated to 180945 damaged buildings.

It is noted that many of the 180945 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 also provided by the National Statistics Agency of Greece (N.S.S.G.) according to the results of the 2000-1 census. Comparing the total number of damaged buildings (180945) to the total number of buildings in the affected area (753078) it is concluded that the dataset addresses to 24,03% of the total local population of buildings, which is a wide and reliable statistical sample.

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 (Karabinis *et al.* 2007, Eleftheriadou *et al.* 2008a, 2008b, Eleftheriadou 2009). In the present paper, 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. 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. 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

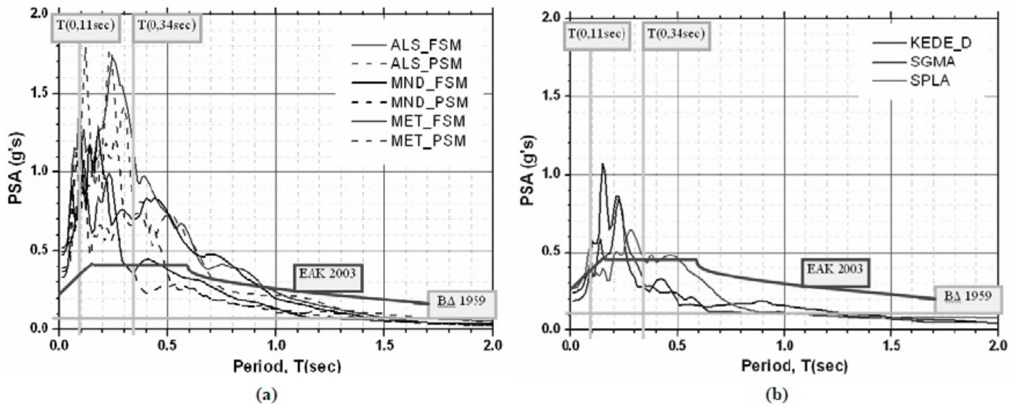

Fig. 2 Elastic acceleration spectra of (α) artificial and (*β*) real seismic ground motions (I.T.S.A.K.-A.U.Th., 2004)

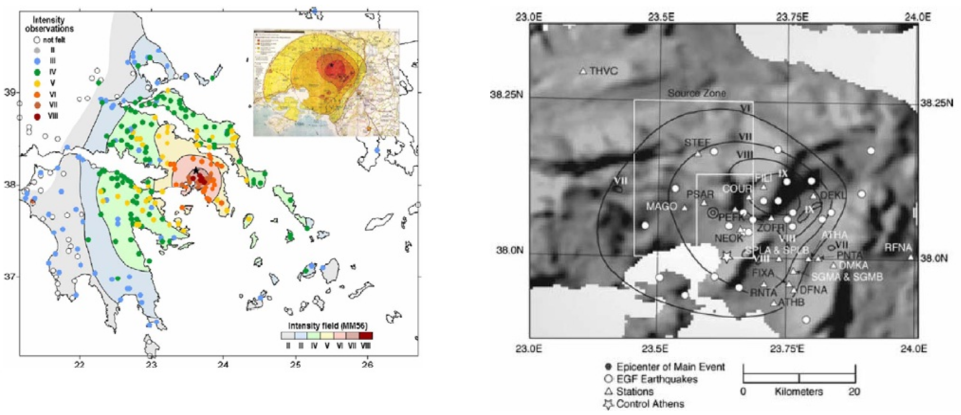

Fig. 3 Existing isoseismal intensity maps (Schenková *et al*. 2007, Hutchings *et al.* 2007)

seismic regulations. Buildings constructed before and after the introduction of the first Seismic Code are often treated similarly in Greece (NTCG 2006).

2. Seismic demand

On the 7th of September, 1999 at 14:56 local time (11:56 GMT), a strong and unexpected earthquake with moderate to strong magnitude, $M = 5.9$, according to the Institute of Geodynamics of the National Observatory of Athens, occurred at a small epicentral distance (18 km) from the historical centre of the city of Athens in Greece, a densely populated area (Ioannidou *et al.* 2001). Simplified expressions for the evaluation of the fundamental period of typical Greek RC buildings with several heights are used in order to be correlated with the spectral accelerations of the specific seismic event. The elastic acceleration spectra of (α) artificial and (*β*) real seismic ground motions are presented in Fig. 2. The evaluated fundamental periods and the elastic spectrum of the first (1959) and the contemporary (2003) Greek seismic code are also presented in the same figure. It is

Table 2 Correlation between macroseismic intensity I and PGA

Intensity I	Peak ground acceleration a_g (cm/sec²)
V (5.0)	41,68
V+ (5.5)	60,34
VI (6.0)	87,36
VI+ (6.5)	126,47
VII (7.0)	183,09
VII+ (7.5)	265,07
VIII (8.0)	383,75
VIII+ (8.5)	555,57
IX (9.0)	804,32

concluded that in the most records the peak ground accelerations (PGAs) were between the lower and the upper bound of the pre - evaluated fundamental periods.

The measure chosen to describe the seismic demand must be capable of representing the earthquake duration, the amplitude, the frequency content, and the influence of source, path and site of the strong ground motion. It should also be evaluated independently of the seismic vulnerability of the building stock on which it is imposed. The independence of seismic hazard with respect to the structural damage can increase the confidence in the risk assessment results. From a general perspective, there are two broad types of parameters, used in engineering, to characterize ground shaking: the seismological intensity parameters, and the quantitative measures of ground shaking. It is important to mention, that the macroseismic scales are subjective. As a result, a more precise characterization of the ground motion can lead to a more reliable earthquake damage prediction. However, the engineering intensity scale has been in use for a long time as it has the advantage of familiarity, it does not need movement sensors, it represents the structural response of structures, and it has been correlated to a sizeable amount of motion - damage data. Nevertheless, its use would require statistical data for all types of structures and a broad range of shaking intensities (Dolce *et al.* 2006).

In the current study the intensity values in the Modified Mercalli Scale have been estimated based on the three following sources (Eleftheriadou 2009, Eleftheriadou *et al.* 2011): (1) The information provided by the Geodynamic Institute of the National Observatory of Athens (NOA) (Kalogeras and Stavrakakis 2001), (2) The results of a research program funded by the Earthquake Planning and Protection Organization that referred to the estimated macroseismic intensities of the meizoseismal area (Gazetas and Collaborators 2001) and (3) The existing isoseismal intensity maps (Fig. 3) which display significant similarity between them (Schenková *et al*. 2007, Hutchings *et al.* 2007). The isoseismal intensity has been compiled from some researchers in the Modified Mercalli Scale (MMS) and from others in the European Macroseismic Scale 1998 (EMS-98). The latter considers additional criteria when compared to MMS, although for the range of values used in the 1999 Athens earthquake the estimated intensities in EMS-98 are quite similar to MMS values. The isoseismal intensity map that is used is consistent with the individual MMS values obtained near most NOA (Institute of Geodynamics, National Observatory of Athens) stations. Therefore, the estimated values of the macroseismic intensity are consistent with the actual records, which describe the ground seismic motion. Intensities (I) and PGA's are correlated using the empirical relationship of Eq. (1) for the area studied.

$$\ln(PGA) = 0.74 * I + 0.03 \tag{1}$$

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, NTCG 2006). The regional macroseismic intensity is defined based on the above mentioned sources. The estimated intensities are afterwards correlated to the peak ground acceleration using Eq. (1). Table 2 presents the evaluated peak ground accelerations (PGAs), after the application of Eq. (1), from the regional estimated macroseismic intensities I (V up to IX). These levels of severity in ground shaking are also presented in the developed Damage Probability Matrices.

The specific equation has been selected in the present paper among others because its validity has been examined in Athens earthquake. The relationship between macroseismic intensities I and PGAs, according to equation 1, has been calibrated for intensities up to IX.

The correlation between I and PGA could make attainable a posterior comparison between the produced vulnerability models and those that are proposed by EPPO. The parameter that characterizes the seismic input, in EPPO models, 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 (National Technical Chamber of Greece 2006).

3. Evaluation of cumulative frequencies and damage probability matrices

The present process satisfies the need of homogeneity in the presented large amount of damage data, all derived after the occurrence of a 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. Despite the fact that DPMs are usually constructed for I≥VI, since for weaker intensities the building damage is almost practically zero, in the produced results V intensity level was not disregarded because this information was available from the intensity values sources and also because a large number of the damaged buildings of the database derived from the weak intensity regions. In addition, there are similar construction practices and soil conditions and the total number of the buildings, in each region, can in this way be determined.

In order to develop DPMs the damaged buildings of the database needed to be classified into structural types. The chosen structural types are on purpose identical to those proposed by the National Statistics Agency of Greece. According to the available information, 73468 buildings with damage characterization could be classified into structural types and subsequently they were subdivided into the five intensity levels (Eleftheriadou *et al.* 2011). 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.

In order to assess seismic vulnerability, it is necessary to obtain the relative frequency, in terms of damage ratio, of different damage states for each structural type exposed to a specific seismic demand. For a given ground motion, the number of buildings of a structural class reaching or exceeding a certain degree of damage in a region has to be normalised to the total number of buildings belonging to the same class and to the same region, an information provided by the General Secretariat of National Statistics Agency of Greece according to the results of the 2000-1 census. The latter is evaluated as the ratio of the number of damaged buildings belonging to a

Table 3 Distribution of the classified buildings into structural types according to the severity of the seismic input and the degree of the structural damage obtained from the 1st or/and the 2nd round (or level) of inspection

		Macroseismic intensity I					
Damage state	Structural type	V	VI	VII	VIII	IX	
Slight (green)	RC1	618	663	7073	1442	755	
	RC2	60	106	619	371	453	
	RC3	11	19	233	163	225	
	MIX1	303	266	2535	565	268	
	MIX2	6	7	51	13	48	
	MIX3	1	3	7	5	11	
	MAS	308	274	1612	419	372	
	OTH	30	47	349	52	176	
Moderate (yellow)	RC1	1096	988	11012	2813	3289	
	RC2	74	120	668	467	1444	
	RC3	6	10	206	167	521	
	MIX1	770	716	6587	1493	1291	
	MIX2	18	19	72	30	140	
	MIX3	0	2	14	4	33	
	MAS	884	945	5612	1153	1425	
	OTH	244	264	1995	282	606	
Extensive (red)	RC1	46	53	234	98	260	
	RC2	2	2	17	13	67	
	RC3	1	1	7	2	25	
	MIX1	46	46	294	79	181	
	MIX2	0	1	120	3	14	
	MIX3	0	1	0	0	7	
	MAS	75	112	514	107	252	
	OTH	73	42	520	92	365	
Collapse (black)	RC1	1	8	126	52	118	
	RC2	0	1	13	8	29	
	RC3	0	0	2	5	10	
	MIX1	16	10	199	68	67	
	MIX2	0	0	7	0	6	
	MIX3	0	0	0	1	0	
	MAS	9	14	293	93	63	
	OTH	7	13	238	63	137	
Total		4705	4753	41229	10123	12658	73468

a_g/a_o		V-V+ (PGA=0.24g: 0.18-0.26)		VI-VI+ (PGA=0.24g: 0.37-0.54)		VII-VII+ (PGA=0.24g: 0.78-1.13)		VIII (PGA=0.24g: 1.63)		IX (PGA=0.24g: 3.42)	
		V-V+ (PGA=0.16g: 0.27-0.38)		VI-VI+ (PGA=0.16g: 0.56-0.81)		VII-VII+ (PGA=0.16g: 1.17-1.69)		VIII (PGA=0.24g: 1.63)		IX (PGA=0.16g: 5.12)	
Damage style	Structural type	1st round	2nd round	1st round	2nd round	1st round	2nd round	1st round	2nd round	1st round	2nd round
Slight (Green)	RC1										
	RC2										
	RC3										
	MLX1										
	MLX2										
	MLX3										
	MAS										
	OTH										
Moderate (Yellow)	RC1										
	RC2										
	RC3										
	MLX1										
	MLX2										
	MLX3										
	MAS										
	OTH										
Extensive (Red)	RC1										
	RC2										
	RC3										
	MLX1										
	MLX2										
	MLX3										
	MAS										
	OTH										
Collapse (Black)	RC1										
	RC2										
	RC3										
	MLX1										
	MLX2										
	MLX3										
	MAS										
	OTH										
											73,468

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 (Table 3). Table 3 presents seismic demand in terms of macroseismic intensity and a ratio of peak ground acceleration, as well. As it has been already mentioned among the 180945 buildings there were many which were not fully described. Hence, the corresponding buildings have been disregarded from the process.

The information from the database refers to qualitative characterizations of damage level used in the post - earthquake surveys in Greece, based on instructions provided by EPPO in 1984 and in 1997 in order to define whether its seismic capacity is adequate against future expected seismic forces.

Furthermore, the qualitative characterization of damage has been correlated to the damage states of a proposed in another research damage scale for the calibration of seismic damage referring to the main structural types of RC buildings (Eleftheriadou *et al*. 2008b, 2010). This scale measures structural damage based on quantitative damage levels, in addition to the descriptive terms of damage, thus producing a structural damage classification. The scale quantifies the severity of damage using, as well, a cost damage index. In the collected data, there was no information about the cost of repairs or the description of damage. For the development of DPMs

Table 4 Evaluated cumulative frequencies for RC1-MIX1

Cumulative frequency (RC1-MIX1)							
Damage state		Central damage factor (%)	Macroseismic intensity I				
			V	VI	VII	VIII	IX
None	DS0	0.125%*N(1)/2+0.50%*N(1)/2	1.0000	1.0000	1.0000	1.0000	1.0000
Green	DS1	0.50%	0.0207	0.0497	0.1448	0.3017	0.5604
Yellow	DS2	15%	0.0141	0.0329	0.0952	0.2101	0.4684
Red	DS3	65%	0.0008	0.0021	0.0044	0.0136	0.0563
Black	DS4	100%	0.0001	0.0003	0.0017	0.0055	0.0166

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

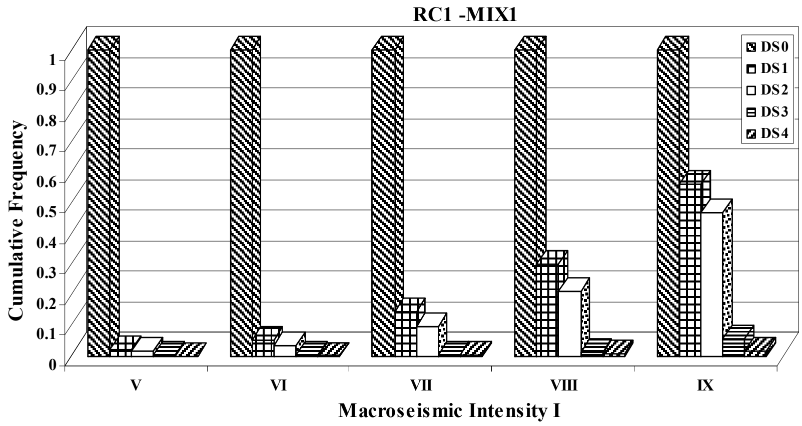

Fig. 3 Evaluated cumulative frequencies for RC1-MIX1

five damage states are defined according to the measurable economic damage index (Kappos *et al.* 1998, 2002, NTCG 2006, Eleftheriadou 2009). The range of damage index in monetary loss for the corresponding five damage states is: (1) 0% - No damage (DS0), (2) 0-1% - Slight damage – Green (DS1), (3) 1-30% - Light-Moderate damage – Yellow (DS2), (4) 30-100% - Extensive damage-Partial Collapse – Red (DS3) and (5) 100% - Collapse – Black (DS4). The Central Damage Factor (CDF) for each damage state is presented in the Tables of the produced DPMs. The *thresholds* of the damage states are in accordance with those proposed by the National Technical Chamber of Greece (2006) and ATC-13 (1985). It has been assumed for the development of damage relationships 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 yield better results (ITSES-AUTh 2004).

The probability of reaching or exceeding each damage state can be estimated simply by cumulating the frequencies from the highest to the lowest level of damage. In the sequence, for each damage state, the statistical data may be rearranged, to show the frequency as a function of the intensity level (Rota *et al.* 2006). In this case the cumulative value of the no damage state is always equal to 1. Relative frequencies have been computed and presented for each building type as it shows in Tables 4 to 8 and Figs. 3 to 7. In the National Statistics Agency of Greece there is no discrimination between RC and MIX building types. The categorization in the typology of buildings is referred regarding the: (a) material of construction (reinforced concrete, masonry, metal or wood or stone or else), (b) year of construction and (c) number of floors. Therefore in

Table 5 Evaluated cumulative frequencies for RC2-MIX2

Cumulative frequency (RC2-MIX2)							
Damage state		Central damage factor (%)	Macroseismic intensity I				
			V	VI	VII	VIII	IX
None	DS0	0.125%*N[(1)]/2+0.50%*N[(1)]/2	1.0000	1.0000	1.0000	1.0000	1.0000
Green	DS1	0.50%	0.0048	0.0165	0.0658	0.1596	0.3134
Yellow	DS2	15%	0.0028	0.0092	0.0377	0.0919	0.2420
Red	DS3	65%	0.0001	0.0003	0.0066	0.0042	0.0165
Black	DS4	100%	0.0000	0.0001	0.0008	0.0014	0.0050

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

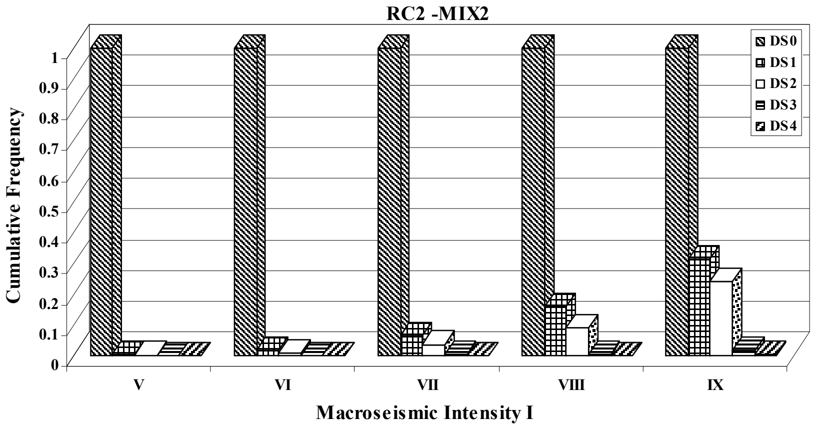

Fig. 4 Evaluated cumulative frequencies for RC2-MIX2

Table 6 Evaluated cumulative frequencies for RC3-MIX3

Cumulative frequency (RC3 – MIX3)							
Damage state		Central damage factor (%)	Macroseismic intensity I				
			V	VI	VII	VIII	IX
None	DS0	0.125%*N[(1)]/2+0.50%*N[(1)]/2	1.0000	1.0000	1.0000	1.0000	1.0000
Green	DS1	0.50%	0.0031	0.0065	0.0347	0.1139	0.2942
Yellow	DS2	15%	0.0011	0.0025	0.0170	0.0588	0.2108
Red	DS3	65%	0.0002	0.0004	0.0007	0.0026	0.0149
Black	DS4	100%	0.0000	0.0000	0.0002	0.0020	0.0035

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

order to produce Damage Probability Matrices the structural types of RC1 and MIX1, RC2 and MIX2, RC3 and MIX3 had to be unified (Eleftheriadou *et al.* 2011). Moreover, buildings constructed before and after the introduction of the first seismic code are often treated similarly in the recent vulnerability models proposed by the National Technical Chamber of Greece (2006). The level of seismic design and detailing in Greece as far as the pre - 1985 *R/C* buildings are concerned constructed without and with code is similar: (1) *No Seismic Code* (or pre – seismic code: before 1959): *R/C* buildings with practical very low level of seismic design and poor quality of detailing. However, it should not be ignored the experience in the construction practices which in many cases could empirically insure important engineering issues. (2) *Low Seismic Code (1959-*

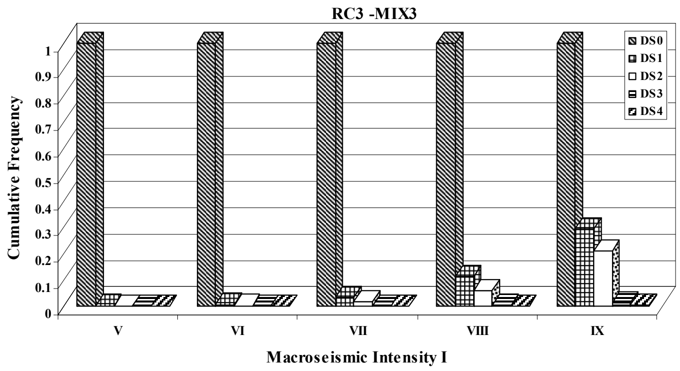

Fig. 5 Evaluated cumulative frequencies for RC3-MIX3

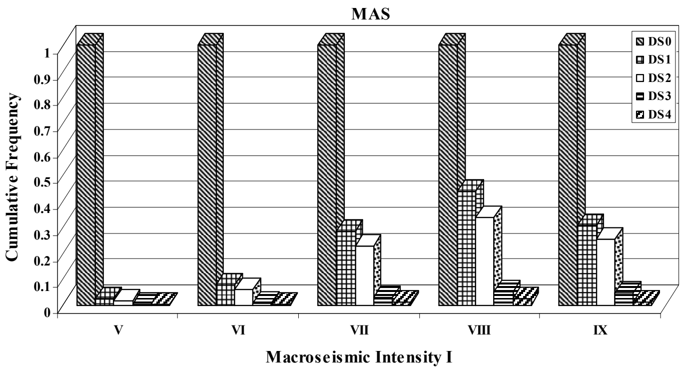

Fig. 6 Evaluated cumulative frequencies for MAS

Table 7 Evaluated cumulative frequencies for MAS

Cumulative frequency (MAS)							
Damage state		Central damage factor (%)	Macroseismic intensity I				
			V	VI	VII	VIII	IX
None	DS0	0.125%*N[(1)]/2+0.50%*N[(1)]/2	1.0000	1.0000	1.0000	1.0000	1.0000
Green	DS1	0.50%	0.0222	0.0751	0.2851	0.4395	0.3080
Yellow	DS2	15%	0.0169	0.0598	0.2279	0.3356	0.2538
Red	DS3	65%	0.0015	0.0070	0.0287	0.0496	0.0459
Black	DS4	100%	0.0002	0.0008	0.0104	0.0231	0.0092

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

Table 8 Evaluated cumulative frequencies for OTH

Cumulative frequency (OTH)							
Damage state		Central damage factor (%)	Macroseismic intensity I				
			V	VI	VII	VIII	IX
None	DS0	0.125%*N[(1)]/2+0.50%*N[(1)]/2	1.0000	1.0000	1.0000	1.0000	1.0000
Green	DS1	0.50%	0.0165	0.0506	0.1388	0.2283	0.2703
Yellow	DS2	15%	0.0151	0.0441	0.1232	0.2040	0.2333
Red	DS3	65%	0.0037	0.0076	0.0339	0.0724	0.1057
Black	DS4	100%	0.0003	0.0018	0.0107	0.0294	0.0288

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

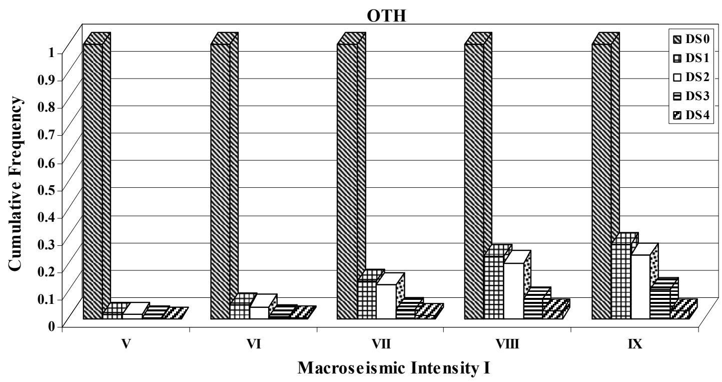

Fig. 7 Evaluated cumulative frequencies for OTH

Table 9 DPM for the RC1-MIX1 Structural Type derived from the available data

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 number of buildings with nearly no damage (4.886 to 165.665 buildings).

Table 10 DPM for the RC2-MIX2 Structural Type derived from the available data

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 number of buildings with nearly no damage (4.764 to 33.034 buildings).

1985: the 1st Seismic Code of 1959): *R/C* buildings with low level of seismic design (corresponding approximately to pre - 1980 codes in Southern Europe).

Finally, 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. For example, 92 RC1-MIX1 buildings with extensive damage (red) and 17 collapses are found in intensity level V, a region with 139794 total number of buildings according to National Statistics Agency of Greece. Therefore, the cumulative probability for the extensive damage level (red) in V intensity level is calculated by the sum of the relative frequencies of each damage state: [(17/139794)*100+ (92/139794)*100]/100 = 0.008. In the same way, the cumulative frequencies have been evaluated for each damage and intensity level for all structural types. For each intensity level a median damage factor (MDF) is evaluated (e.g. for RC1-MIX1 structural type in V intensity level: MDF = 0.125*(97.93/2)/100+0.5*(97.93/2)/100+0.5*0.66/100+15*1.33/100+65*0.07/100+100*0.01/100 =0.56).

Table 11 DPM for the RC3-MIX3 Structural Type derived from the available data

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 number of buildings with nearly no damage (1.996 to 13.040 buildings).

Table 12 DPM for the MAS Structural Type derived from the available data

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%	14.57%
% of the data to the total population			2.22	7.51	28.51	43.95	30.80

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

Table 13 DPM for the OTH Structural Type derived from the available data

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 number of buildings with nearly no damage (1.653 to 21.114 buildings).

Table 14 Distribution of the proportional damaged buildings according to the severity of the seismic input

		Macroseismic intensity I (MMS)					
Damage state	Structural type	V	VI	VII	VIII	IX	
Slight (green)	RC1	4746	3774	40524	6365	4293	
	RC2	368	551	3297	1651	2483	
	RC3	77	71	1231	784	1258	
	MIX1	2284	1606	13405	3048	1533	
	MIX2	17	20	191	68	264	
	MIX3	88	7	36	34	64	
	MAS	1366	1189	8463	2056	2157	
	OTH	164	245	1672	229	1008	
Moderate (yellow)	RC1	1283	1265	13338	3213	4142	
	RC2	83	212	1344	542	1817	
	RC3	7	39	248	197	661	
	MIX1	864	948	7721	1703	1642	
	MIX2	24	18	84	35	177	
	MIX3	1	2	16	5	41	
	MAS	1074	988	6337	1340	1825	
	OTH	255	277	2339	322	770	
Extensive (red)	RC1	56	66	409	154	185	
	RC2	2	2	36	22	140	
	RC3	1	2	13	3	52	
	MIX1	51	59	469	117	378	
	MIX2	0	1	140	5	51	
	MIX3	0	1	0	0	14	
	MAS	90	134	766	184	536	
	OTH	70	68	785	140	785	
Collapse (black)	RC1	1	12	190	87	221	
	RC2	0	1	19	16	55	
	RC3	0	0	3	9	18	
	MIX1	17	17	288	123	127	
	MIX2	2	0	10	0	11	
	MIX3	0	0	0	1	0	
	MAS	12	34	415	157	119	
	OTH	10	25	334	109	262	
Total		13013	11634	104123	22719	27089	178578

In Tables 9 to 13 the produced DPMs are presented concerning the pre - described structural types which were derived from the damage dataset with 73468 buildings (Eleftheriadou 2009, Eleftheriadou *et al.* 2011). It must be mentioned that there is no discrimination between the RC and Mixed buildings in the structural types provided by the National Statistics Agency 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 a 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 the most intensity levels and the evaluated median damage factors

(MDFs) of these levels are the most reliable. The number of buildings with nearly no damage, represented by number *N* in each Table, differs in each intensity level. In Tables 9 to 13 the lower and upper boundary of *N* is given at footnotes.

It shouldn't be ignored that the produced DPMs were derived from the available real data of 73468 damaged buildings. It was available the necessary information for the subdivision of these buildings according to the structural types, the damage characterization and the seismic input.

However, in the developed damage database, 180427 buildings had the characterisation of

Table 15 DPM for the RC1-MIX1 Structural type derived from the proportional data

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	93.35%	86.00%	60.59%	32.41%	0.00%
Green	DS1	0.50%	5.03%	9.72%	27.84%	42.96%	46.53%
Yellow	DS2	15%	1.53%	4.00%	10.87%	22.43%	46.19%
Red	DS3	65%	0.08%	0.23%	0.45%	1.24%	4.50%
Black	DS4	100%	0.01%	0.05%	0.25%	0.96%	2.78%
Median damage factor (MDF)			0.61%	1.12%	2.50%	5.44%	12.86%
% of the data to the total population			6.65	14.00	39.41	67.59	100.00

[(1)] Where *N* is the number of buildings with nearly no damage (nearly undamaged).

Table 16 DPM for the RC2-MIX2 Structural type derived from the proportional data

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	98.50%	94.82%	78.49%	58.74%	28.84%
Green	DS1	0.50%	1.16%	3.67%	14.65%	30.32%	39.11%
Yellow	DS2	15%	0.32%	1.48%	6.00%	10.18%	28.39%
Red	DS3	65%	0.01%	0.02%	0.74%	0.48%	2.72%
Black	DS4	100%	0.01%	0.01%	0.12%	0.28%	0.94%
Median damage factor (MDF)			0.37%	0.56%	1.82%	2.45%	7.25%
% of the data to the total population			1.49	5.18	21.51	41.26	71.16

[(1)] Where *N* is the number of buildings with nearly no damage (nearly undamaged).

Table 17 DPM for the RC3-MIX3 Structural type derived from the proportional data

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	97.16%	97.79%	88.55%	66.10%	25.46%
Green	DS1	0.50%	2.69%	1.41%	9.38%	26.84%	46.75%
Yellow	DS2	15%	0.13%	0.74%	1.95%	6.63%	24.82%
Red	DS3	65%	0.02%	0.06%	0.10%	0.10%	2.33%
Black	DS4	100%	0.00%	0.00%	0.02%	0.33%	0.64%
Median damage factor (MDF)			0.35%	0.46%	0.70%	1.73%	6.19%
% of the data to the total population			2.84	2.21	11.45	33.90	74.54

[(1)] Where *N* is the number of buildings with nearly no damage (nearly undamaged).

damage. The assumption that the buildings which could not be 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 posterior procedure was followed in order to include the remaining buildings, which were not initially 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. This was achieved by extending the same proportions of damage distribution associated with the 73468 buildings, into the 178578 buildings (Table 14).

Following this procedure, new *proportional* DPMs were produced, including the proportioned number of 178578 buildings (Tables 15 to 19). 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.

In order to conduct a correlation analysis Tables 20 to 23 are presented with the results of the

Table 18 DPM for the MAS Structural type derived from the proportional data

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	95.58%	86.91%	43.27%	7.32%	32.38%
Green	DS1	0.50%	2.38%	6.64%	30.04%	50.99%	31.46%
Yellow	DS2	15%	1.87%	5.51%	22.50%	33.24%	26.61%
Red	DS3	65%	0.15%	0.75%	2.72%	4.56%	7.82%
Black	DS4	100%	0.02%	0.19%	1.47%	3.89%	1.73%
Median damage factor (MDF)			0.71%	1.81%	6.90%	12.12%	22.32%
% of the data to the total population			4.42	13.09	56.73	92.68	67.62

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

Table 19 DPM for the OTH Structural type derived from the proportional data

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	97.67%	91.49%	77.05%	62.65%	40.53%
Green	DS1	0.50%	0.76%	3.39%	7.48%	10.69%	21.22%
Yellow	DS2	15%	1.19%	3.83%	10.47%	15.03%	16.21%
Red	DS3	65%	0.33%	0.94%	3.51%	6.54%	16.53%
Black	DS4	100%	0.05%	0.35%	1.49%	5.09%	5.51%
Median damage factor (MDF)			0.75%	1.83%	5.63%	11.84%	18.92%
% of the data to the total population			2.32	8.51	22.95	37.35	59.47

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

Table 20 Comparison between existing DPMs for RC buildings designed earlier than 1985

	Intensity I		VI	VII	VIII	IX
			Median damage factor (MDF) %			
Proposed DPM	Available data		0,92	2,00	4,28	10,61
	Proportional data		1,12	2,50	5,44	12,86
DPM Volos (National Technical Champer Greece 2006)	Frame-wall/Without pilotis/Regular infills	Low height	1,12	1,68	6,03	10,86
		Medium height	1,07	1,54	5,50	10,68
		High height	0,51	1,86	7,46	15,75
	Frame-wall/With pilotis/Regular infills	Low height	1,23	1,34	9,62	16,40
		Medium height	1,14	1,57	8,23	15,06
		High height	0,50	1,71	5,98	17,06
DPM Athens (National Technical Champer Greece 2006)	Frames/Without pilotis/Regular infills	Low height	4,40	20,50	48,20	71,10
		Medium height	0,50	2,40	10,00	29,10
		High height	2,00	11,50	30,70	51,10
	Frame-wall/Without pilotis/Regular infills	Low height	1,10	6,20	21,70	48,50
		Medium height	0,50	2,40	10,00	29,10
		High height	1,10	4,90	12,00	19,60
	Frames/With pilotis/Regular infills except for ground floor	Low height	12,00	36,60	63,40	77,00
		Medium height	28,30	58,80	76,10	79,70
		High height	1,70	8,80	25,50	50,20
	Frame-wall/With pilotis/Regular infills except for ground floor	Low height	1,10	6,10	21,90	49,20
		Medium height	0,80	4,80	17,20	40,80
		High height	0,90	3,50	9,50	18,90
	Frames/Without infills	Low height	15,10	39,90	65,20	77,40
		Medium height	16,30	45,80	70,80	79,10
		High height	3,70	14,40	34,70	59,30
	Frame-wall/Without infills	Low height	3,10	12,40	32,30	57,90
		Medium height	2,80	9,20	23,50	46,70
		High height	3,00	7,50	14,10	21,50

Table 21 Comparison between existing DPMs for RC buildings designed during the period 1985-1995

	Intensity I		VI	VII	VIII	IX
			Median damage factor (MDF) %			
Proposed DPM	Real data		0,46	1,23	1,94	4,88
	Proportional data		0,56	1,82	2,45	7,25
DPM Volos (National Technical Champer Greece 2006)	Frame-wall/Without pilotis/Regular infills	Low height	0,65	1,12	1,91	5,70
		Medium height	0,61	1,03	1,71	5,32
		High height	0,50	1,24	5,05	9,68
	Frame-wall/With pilotis/Regular infills	Low height	0,71	1,23	2,14	7,88
		Medium height	0,62	1,20	2,19	7,72
		High height	0,50	1,41	4,55	14,13

existing vulnerability studies which have been adopted by the National Programme for Earthquake Management of Existing Buildings and the National Technical Chamber of Greece (2006). These studies have been conducted in Volos and Athens which are areas with similar soil condition and construction practices to the area studied.

Table 22 Comparison between existing DPMs for RC buildings designed after 1995

Intensity I			VI	VII	VIII	IX
			Median damage factor (MDF) %			
Proposed DPM	Real data		0,37	0,60	1,39	4,29
	Proportional data		0,46	0,70	1,73	6,19
DPM Athens (National Technical Champer Greece 2006)	Frames/Without pilotis/Regular infills	Low height	0,50	2,20	7,30	20,40
		Medium height	0,30	1,40	5,40	17,50
		High height	0,40	1,90	5,80	16,10
	Frame-wall/Without pilotis/Regular infills	Low height	0,10	0,70	3,60	14,20
		Medium height	0,30	1,40	5,40	17,50
		High height	0,20	0,50	1,70	5,90
	Frames/With pilotis/Regular infills except for ground floor	Low height	0,40	3,10	14,00	39,10
		Medium height	0,80	5,30	22,80	55,00
		High height	0,20	1,10	6,30	23,00
	Frame-wall/With pilotis/Regular infills except for ground floor	Low height	0,10	0,60	3,00	12,40
		Medium height	0,30	1,50	6,40	19,80
		High height	0,10	0,60	2,00	6,00
	Frames/Without infills	Low height	3,30	9,90	26,40	53,00
		Medium height	3,20	8,50	18,20	36,20
		High height	0,60	2,00	4,90	13,30
	Frame-wall/Without infills	Low height	0,10	1,00	4,50	17,10
		Medium height	0,50	2,40	8,20	23,20
		High height	0,20	0,50	1,50	5,40

Table 23 Comparison between existing DPMs for masonry buildings

Intensity I			VI	VII	VIII	IX
			Median damage factor (MDF) %			
Proposed DPM	Real data		1,57	5,47	8,55	14,57
	Proportional data		1,81	6,90	12,12	22,32
DPM Volos (National Technical Champer Greece 2006)	Unreinforced masonry	1-3 floors	5,06	12,86	26,27	47,82
	Unreinforced masonry	4-7 floors	5,06	12,93	30,54	53,25
DPM Athens (National Technical Champer Greece 2006)	Brick masonry	1-2 floors	0,40	9,80	48,00	80,60
	Stone masonry	1-2 floors	3,00	16,10	48,00	77,80
	Brick or stone masonry	3+ floors	0,00	1,30	13,80	49,40

6. Conclusions

The development of a systematic method in the recording of damage after a major earthquake can contribute to the improvement of seismic security (government policies and regulations for management of the seismic risk). The current research focuses on the empirical seismic vulnerability assessment of typical building types, representative of the materials, the seismic codes and the construction techniques used in Greece, and generally in Southern Europe, based on processing of a large set of observational data. The study constitutes a sequel of a previous research. A wider damage database (178578 buildings) is created compared to the Damage Probability Matrices (DPMs) of the first presented paper (73468 buildings) after the elaboration of the results from post - earthquake surveys carried out after the 7-9-1999 near field Athens earthquake. The seismic demand is both described by estimating the macroseismic intensity of each municipality and by estimating the ratio of the max peak ground acceleration (PGA) of a certain earthquake event to the PGA that each municipality was characterized the date of each building's construction. The damaged buildings are distributed for each building type according to the degree of damage and the level of severity of the ground motion. The relative and the cumulative frequencies of the different damage states, for each structural type and each intensity level, are computed and presented, in terms of damage ratio. A procedure is presented for the classification of the buildings with restricted information which initially had been disregarded and new *proportional* Damage Probability Matrices (DPMs) are developed for typical structural types. A correlation analysis is fulfilled between the produced *proportional* and the existing vulnerability models in areas with similar soil conditions and construction practices.

The correlation of the damage surveyed areas with the real ground motion records or the macroseismic intensity of existing isoseismal maps is the first step in conducting a vulnerability assessment. In addition, the data obtained from a region with a certain level of seismic intensity severity signify the local distribution of the extent of damage was allowing disaster management professionals to develop and define the criteria for prioritizing seismic strengthening (rehabilitation) programs for existing buildings. Decisions regarding the seismic rehabilitation of existing buildings require both engineering and economic studies and consideration of social priorities. Pre- and post-earthquake upgrading of a city's existing building stock is one of the most challenging tasks in public policy decisions.

Important and realistic conclusions are extracted from the elaboration of the damage observational database as it includes the real response of the buildings after a near field earthquake. In particular, RC and MIX building types exhibited overall better seismic performance in the referring earthquake compared to masonry buildings. In addition, the damaged buildings which have been designed and constructed according to older seismic codes developed more severe 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 older codes. This is a significant problem when one considers that the majority of the existing buildings are constructed using older regulations. The sufficient management of seismic risk becomes urgent.

The obtained relationships derived from the empirical seismic vulnerability assessment of this research (Tables 9 to 13 and 15 to 19), are applicable to seismic risk analysis and scenarios and in general, to earthquake mitigation policies. After conducting a correlation analysis with the existing DPMs proposed by National Technical Champer Greece (2001 and 2006) it derives that the produced results do not essentially differ from them. This conclusion is more obvious especially when the intensity levels with the most numerous damaged buildings are examined, although they do not refer to exactly the same structural types. It must be pointed out that if the existing DPMs, coming from different vulnerability studies, are compared with them they present a noticeable difference between the results referring to the same structural types. Despite the fact that the produced DPMs refer to a wide variety of structural types, they depend on parameters that are important in the seismic response.

The main differences connected to the buildings classification are related to the height, the lack of infills on the ground floor (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 (National Technical Champer Greece 2006), whereas the information about MRF or mixed buildings is not available in the structural types proposed by the National Statistics Agency of Greece. After the comparison between the existing DPMs derived from different vulnerability studies, it is noted that they also present a distinct difference among the same structural types. Note that the DPMs recently proposed by the NTCG in 2006 have been modified over time from those that were initially proposed in 2001. The NTCG vulnerability curves have been derived from a hybrid approach, which combines statistical data with appropriately processed results from nonlinear dynamic or static analyses, that permit extrapolation of statistical data to PGA's and/or spectral displacements for which no data are available. The hybrid approach has been adopted in recognition of the fact that reliable statistical data for seismic damage are quite limited and typically correspond to a very small number of intensities. Damage data that was collected from Greek earthquakes although valuable was generally not in a form such that economic damage statistics could be assessed for a representative set of buildings. Moreover, even the good quality data for Thessaloniki's 1978 earthquake was corresponded to a single intensity estimated level at about VII (MSK). Data from abroad had then to be imported, or the available data should be augmented using either expert judgement (ATC 1985) or an analytical (mechanical) approach. The Greek hybrid methodology was based on a combination of the empirical/statistical and the analytical/mechanical approach. Thus, the existing Greek EPPO DPMs for I > VII are based on theoretical analysis (Dolce *et al.* 2006).

Analyzing the results it is concluded that: (1) The DPM developed for the RC1-MIX1 structural type is very similar to those produced in the vulnerability study of Volos (Kappos *et al.* 2002) for all structural types and especially for the DPM of frame - wall structural system without pilotis and with regular infills (NTCG 2006). The Median Damage Factor values are also close, for low intensity levels, to the DPMs of ITSES-AUTh (2004) for buildings with medium height with frame - walls or frames, without pilotis and with regular infills. On the contrary, they are quite different for high intensities, wherein the produced DPMs have lower MDF values. **2.** The DPM produced for the RC2-MIX2 structural type presents good agreement with the referred in the vulnerability study of Volos DPMs for all building types. Only a few variations appear in the higher levels of the seismic input. **3.** The DPMs produced for the RC3-MIX3 structural type is similar to the DPMs for tall buildings with frame - wall structural system for all types of infills (regular infills – no infills – pilotis) (ITSES-AUTh 2004). They differ in high intensities where the DPMs presented herein show lower Median Damage Factor values. The issue is the same as far as the masonry buildings are concerned. The previously mentioned differences are possibly due to the unreliable statistical sample in high intensity levels (a larger number of buildings in VII level and fewer buildings in IX).

It is believed that the wide created homogeneous observational database adds to the reliability of the collected information and reduces the scatter on the produced results. The resulting conclusions verify the presented methodology in practice for the empirical vulnerability assessment. However, the DPMs produced in this study 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 a 1:1 scale after the occurrence of a medium to large magnitude near field seismic event in an extended densely populated urban region. It is considered that the derived vulnerability relationships could represent, in a reliable way, the mean values of the prediction of damage distribution for selected typical classes of buildings in Greece and, generally, in Southern Europe.

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