Earthquakes and Structures, Vol. 3, No. 2 (2012) 117-140
DOI: http://dx.doi.org/10.12989/eas.2012.3.2.117

Seismic vulnerability assessment of buildings based on damage data after a near field earthquake (7 September 1999 Athens - Greece)

Anastasia K. Eleftheriadou* and Athanasios I. Karabinis

Laboratory of RC, Department of Civil Engineering, Democritus University of Thrace, B.Sofias 12, Xanthi 67100, Greece

(Received May 26, 2011, Revised October 29, 2011, Accepted October 31, 2011)

Abstract. The proposed research includes a comprehensive study on the seismic vulnerability assessment of typical building types, representative of the structural materials, the seismic codes and the construction techniques of Southern Europe. A damage database is created after the elaboration of the results of the observational data obtained from post-earthquake surveys carried out in the area struck by the September 7, 1999 Athens earthquake, a near field seismic event in an extended urban region. The observational database comprises 180.945 buildings which developed damage of varying degree, type and extent. The dataset is elaborated in order to gather useful information about the structural parameters influence on the seismic vulnerability and their correlation to the type and degree of building damages in near field earthquakes. The damage calibration of the observational data was based on label - damage provided by Earthquake Planning and Protection Organization (EPPO) in Greece and referred to the qualitative characterization for the recording of damage in post-earthquake surveys. Important conclusions are drawn on the parameters that influence the seismic response based on the wide homogeneous database which adds to the reliability of the collected information and reduces the scatter on the produced results.

Keywords: seismic vulnerability; observational earthquake damage; damage statistics; post-earthquake surveys; Athens earthquake; existing buildings

1. Introduction

The catastrophic impacts of recent earthquakes in areas with densely concentrated population and buildings, such as most of the European town centres, witnessed that these areas are highly exposed to human and economic losses when these centres are situated in seismic regions. Many seismic risk assessments (D' Ayala *et al.* 1997, Faccioli *et al.* 1999, Kappos *et al.* 2002, Dolce *et al.* 2003, 2006) and vulnerability studies (Rossetto and Elnashai 2003, Sarabandi *et al.* 2003, Carreño *et al.* 2004, ITSAK-AUTh 2004, Lagomarsino and Giovinazzi 2006, Kappos 2007, Karabinis and Eleftheriadou 2007, Rota *et al.* 2008, Eleftheriadou and Karabinis 2008a, 2008b, 2011, Eleftheriadou 2009) have been carried out. Their results could turn out important tools in the mitigation of losses due to future seismic events, e.g. allowing disaster management plans to be drawn up. The seismic vulnerability of a building can be defined as its proneness to be damaged by an earthquake. Seismic

* Corresponding author, Ph.D., E-mail: aelefthe@civil.duth.gr

vulnerability relationships attempt to predict for several building classes the degree and the extent of damage at given levels of seismic demand. This is a key step in the preparation of seismic scenarios of a given earthquake providing the results when such an earthquake occurs (Dolce *et al.* 2003).

Reliable earthquake loss estimation (in monetary terms) for buildings struck by an earthquake is of growing importance both for the planning of appropriate and cost effective earthquake mitigation measures and for insurance purposes, and also for the definition of criteria for prioritizing seismic strengthening (rehabilitation) programmes for the existing buildings. Decisions regarding the seismic rehabilitation of 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 conflictual and difficult types of public policy decisions.

The methods of vulnerability assessment can be generally classified into four groups (Fig. 1): judgement-based, empirical/statistical, analytical and hybrid methods, depending on the sources of damage information. Judgement-based method relies on the statistical treatment of the knowledge provided by a team of experts and it depends on the subjective experience. 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. 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. Empirical methods use the distribution of damage reported in post-earthquake surveys as their source and treat these data according to statistical procedures (Rossetto and Elnashai 2003). Score assignment method, which constitutes a sub-method of empirical/statistical, signifies seismically hazardous buildings by defining scores in several structural deficiencies. They often form the first phase of a multi-phase procedure for identifying hazardous buildings which then must

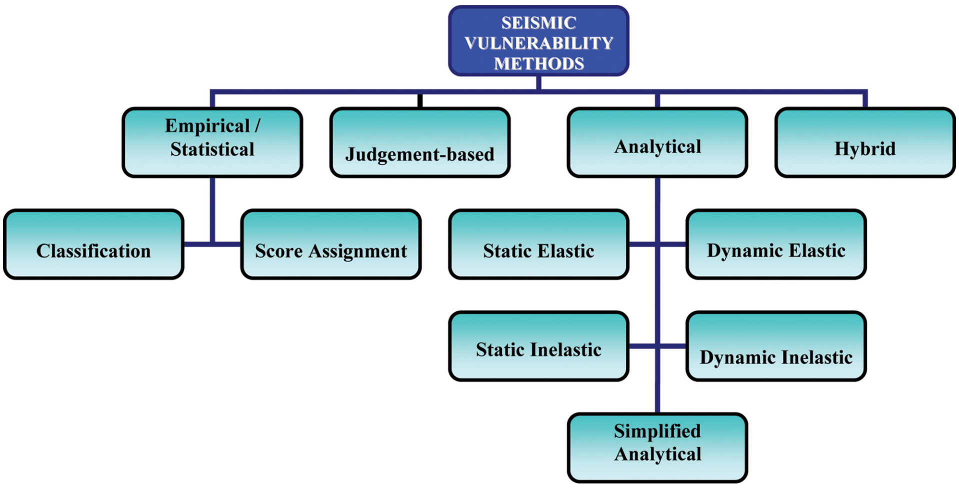

Fig. 1 Seismic vulnerability methods

be analysed in more detail in order to decide on upgrading strategies. Potential structural deficiencies are identified from observed correlations between damage and structural characteristics. 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). For obvious reasons, the observational source is the most realistic as it represents a physical experiment in a 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. In this case, the difficulty derives from 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 and Elnashai 2003, Rota *et al.* 2008, ITSAK-AUTh 2004, Lagomarsino and Giovinazzi 2006, Eleftheriadou and Karabinis 2008b, 2011, Eleftheriadou 2009).

The building inventory varies in extent and quality within the main existing damage data in Greece. The main databases have been derived after the earthquakes of (Panagopoulos and Kappos 2009): 1978 in Thessaloniki with 5.470 damaged buildings (Penelis *et al.* 1989), 1986 in Kalamata with 7.100 damaged buildings (Andrikopoulou 1989), 1995 in Aegion with 2.014 damaged buildings (Karantoni and Fardis 2004), 1999 in Athens with (a) 988 damaged buildings in Ano Liosia (Kappos *et al.* 2007), (b) 2.149 records (ARISTION research programme: 'Ethniki Asfalistiki' insurance company - Vlahos and Vlahos 2008), (c) 664 reinforced concrete buildings (ARISTION research programme: Earthquake Planning and Protection Organization - Katsikas 2006), (d) 3.723 damaged buildings in Aharnes (Karabinis and Baltzopoulou 2006) and finally e) the presented here 180.945 damaged buildings after the creation of the largest in volume database (Eleftheriadou 2009, Eleftheriadou and Karabinis 2008b, 2008c, 2011).

The major damages which developed the existing buildings during the recent earthquakes proved that some specific reasons which are correlated with the development of seismic damage are repeated every time that an earthquake occurs. Despite the fact that a wide investigation was conducted in several regions with similar building stock where major earthquakes (Table 1)

Table 1 Major recent earthquakes in Greece

Region	Date	Magnitude (R)	Impacts
Kalamata	13-9-1986	6,0	20 casualties, 80 injuries, 4 collapses of multi-storey buildings in Kalamata. Total collapse of Elaioxori village. The 20% of the total number of 9.124 buildings of Kalamata were under demolition. Heavy damages in villages.
Kozani-Grevena	13-5-1995	6,6	Extensive damages. Many collapses of buildings in the near distance villages.
Aigio	15-6-1995	6,1	26 casualties, a hotel and a multi-storey building collapsed. Extensive damages.
Konitsa	26-7-1996	5,2	Extensive damages. Many damaged buildings in the town of Konitsa and in the near distance villages.
Athens	7-9-1999	5,9	143 casualties, 1000 injuries, 85 people were rescued from the debris, thousands of homeless. Extensive damages in north-west and south-west suburbs of Athens, many collapses, 180.945 buildings with varying degree, type and extent of damage (after the elaboration of 535.152 reports of inpections). The worst natural disaster (in loss assessment) reported in the modern history of Greece.

occurred in Greece during the last few decades and in the files of institutions or government committees connected to the management of seismic hazard in order to collect damage data the research was focused on the September 7, 1999 Parnitha's earthquake. The reason was that the damage statistics from the pre-mentioned earthquake reached almost six hundred of thousands records. Subsequently, the study was focused on processing the enormous amount of the collected files arising to 535.152 recorded damages. The aforementioned data is considered worldwide among the largest datasets and it has been derived from Athens post-earthquake surveys carried out in the area struck by the Parnitha's earthquake, a near field seismic event in an extended urban region.

2. The September 7, 1999 Parnitha's earthquake

A near field earthquake with moderate to large magnitude, $M = 5{,}9R$ (according to the Institute of Geodynamics of the National Observatory of Athens) occurred on the 7th of September, 1999 at 14:56 local time (11:56 GMT) with epicentral distance of 18 km from the historical centre of the city of Athens in Greece. Athens is situated on hilly ground surrounded by mountains. The mountains are made up of preneogene rocks: massive limestone and dolomites overlie softer schists, conglomerates and limestone. The flat part of the city lies on neogene lacustrine deposits blanketed by terrestrial formations and recent deposits. Of special interest are the recent deposits. They persist along the Kifissos and Ilissos Rivers, consisting mainly of low plasticity clays and clayey sands with a maximum estimated thickness of 10-15 m and in the meizoseismal area of the earthquake (e.g. Ano Liosia and Menidi), with thickness no more than five meters, respectively.

The epicenter is located south of the mountain Parnitha, close to the Saronikos Gulf. The obtained fault plane solution represented normal faulting indicating an almost north-south extension. The calculated source duration is 5 sec, while the estimated dimensions of the fault are 15 km length and 10 km width. The source process is characterized by unilateral eastward rupture propagation, towards the city of Athens. The meizoseismal area was considered before this seismic event as of low seismic activity. Although the earthquake magnitude was moderate, the damage was very serious, since the intensity reached IX. An evident stop phase observed in the recordings is interpreted as a barrier caused by the Aegaleo Mountain (Papadimitriou 2002).

Over a hundred of buildings collapsed and thousands sustained considerable damage, causing 143 casualties, about 1000 injuries and thousands of people became homeless. From the point of view of economic loss, it is the worst natural disaster reported in the modern history of Greece. The most serious damages were observed at the northern suburbs, which are closer to the epicentral area. Damage displayed significant differentiation from place to place, as well as a peculiar geographic distribution. Based on geological, tectonic and morphological characteristics of the affected area and on the elaboration of damage recordings for intensity evaluation, it has been suggested that intensity distribution was the result of the combination of a number of parameters. On the one hand, the parameters are the strike of the seismogenic fault, seismic wave directivity effects and an old NNE±SSW tectonic structure, and they are also responsible for the maximum intensity arrangement in two perpendicular directions ESE±WNW and NNE±SSW. On the other hand, site foundation formations, old tectonic structures buried under recent formations and morphology are the parameters that differentiated intensities within the affected area (Lekkas 2001). Generally, the unlike damage distribution of the 1999 Athens earthquake reflected the destructive combination of two factors: the source directivity and the site effect (Roumelioti *et al*. 2004).

Table 2 Estimated macroseismic intensity values according to the Modified Mercalli Scale

No	Municipality	MMS (I)	No	Municipality	MMS (I)
1	AG. DIMITRIOS[1]	V+	60	KORIDALOS[1]	VII
2	AG. BARBARA[3]	VII	61	KRIONERI[1]	III
3	AG. PARASKEVI[3]	V	62	KROPIA[3]	VI
4	AG. IOANNIS RENTI[3]	VII	63	LAVREOTIKI[3]	V
5	AG. STEFANOS[3]	V	64	LIKOVRISI[3]	VIII
6	AG. ANARGIROI[3]	VIII	65	MAGOULAS[1]	VII
7	AGISTRI[3]	V	66	MALAKASA[3]	V
8	ATHENS[3]	VII	67	MANDRA[3]	VI
9	EGALEO[1]	VII	68	MARATHONAS[3]	V
10	EGINA[1]	V+	69	MARKOPOULO[1]	V+
11	ALIMOS[1]	VI	70	MEGARA[1]	VI
12	MAROUSI[3]	VI	71	MELISIA[1]	V+
13	AMPELAKIA[3]	VI	72	METAMORFOSI[1]/[2]	**VIII**/VIII$^+$-VII$^-$
14	ANABYSOS[3]	V	73	MOSXATO[3]	VII
15	ANTHOYSA[3]	V	74	NEA ERITHREA[1]	VII
16	ANIXI[3]	VI	75	NEA IONIA[1]	VII
17	ANO LIOSIA[1]/[2]	**IX**/IX$^-$-VII	76	NEA FILADELFIA[1]	VIII
18	ARGIROUPOLI[3]	V	77	NEA MAKRI[3]	V+
19	ARTEMIDA[3]	V	78	NEA PENTELI[1]	V+
20	ASPROPIRGOS[1]	VII+	79	NEA PERAMOS[1]	VII
21	AVLONA[1]	V+	80	NEA SMIRNI[3]	VI
22	AFIDNES[1]	V+	81	NEA HALKIDONA[3]	VII
23	AXARNES[1]/[2]	**IX**/IX$^-$-VII	82	NEO IRAKLIO[3]	VII
24	BIRONAS[1]	V+	83	NEO PSIHIKO[3]	VI
25	BARI[1]	V+	84	NEA PALATIA[1]	V+
26	BARNABAS[1]	V+	85	NIKAIA[1]	VII
27	BILIA[1]	V+	86	INOI[3]	VI
28	BOULA[1]	V+	87	PALEO FALIRO[3]	VI
29	BOULIAGMENI[3]	V	88	PEANIA[1]	V+
30	BRILISIA[1]	V+	89	PALEA FOKEA[3]	V
31	GALATSI[1]	VII	90	PALINI[1]	VI
32	GERAKAS[3]	V	91	PAPAGOS[3]	V
33	GLIKA NERA[3]	V	92	PEIREUS[3]	VII
34	GLIFADA[3]	V	93	PENTELI[3]	V
35	GRAMATIKO[1]	V+	94	PERAMA[3]	VI+
36	DAFNI[3]	VI	95	METOHI[3]	VIII
37	DERBENOXORIA[3]	V	96	PERISTERI[2]/[3]	VII$^+$-**VII**/VII
38	DIONISOS[3]	V	97	PETROUPOLI[1]/[2]	**VIII**/VII$^+$-VI$^+$
39	DRAPETSONA[3]	VI+	98	PEFKI[3]	VIII
40	DROSIA[1]	V	100	POLIDENDRI[3]	V
41	EKALI[1]	V+	101	RAFINA[3]	V
42	ELEYSINA[1]	VII	102	RODOPOLI[3]	V+
43	ELINIKO[3]	V	103	SALAMINA[1]	V+
44	ERITHRES[1]	V+	104	SKALA OROPOU[3]	V
45	ZEFIRI[3]	VIII	105	SARONIDA[3]	V
46	ZOGRAFOU[3]	V	106	SPATA[3]	V
47	ILIOUPOLI[3]	V	107	STAMATA[3]	V
48	THIVA[3]	V	108	SIKAMINO[3]	V
49	THRAKOMAKEDONES[1]	IX	109	TAVROS[3]	VII
50	ILIO[1]	VII	110	IMITOS[3]	VI
51	KAISARIANI[3]	V	111	FILOTHEI[1]	V+
52	KALAMOS[3]	V	112	FILI[1]	VIII
53	KALITHEA[3]	VII	113	HAIDARI[1]	VII
54	KALIVIA THORIKOY[1]	V	114	HALANDRI[3]	VII
55	KAMATERO[1]/[2]	**VIII**/VII-VI$^+$	115	HOLARGOS[3]	V
56	KAPANDRITI[3]	V	116	PSIHIKO[3]	VI+
57	KERATEA[1]	V+	117	OROPOS[1]	V+
58	KERATΣINI[3]	VII			
59	KIFISIA[1]	VI+			

[1]Geodynamic Institute of the National Observatory of Athens (Kalogeras and Stavrakakis 2001).
[2]Research programme referring to the meizoseismal area (Gazetas and collaborators 2001).
[3]Isoseismal intensity maps (Schenková *et al.* 2007, Hutchings *et al.* 2007).

Surprisingly heavy damage occurred on the eastern bank of the Kifissos River canyon. A number of these buildings suffered partial or total collapse, while many others were severely damaged. Despite the particular geometry of the slope of about 60 m in height that caused significant motion amplification, topography effects alone cannot explain the disparity in damage distribution which is characterized by a rather uniform structural quality. Soil stratigraphy and material heterogeneity on the topographic aggravation of surface ground motion played important role. Several simulations showed that topographic effects are substantial only within about 50 m from the canyon ridge, materializing primarily because of the presence of relatively soft soil layers near the surface of the profile. The results showed that both topography and local soil conditions significantly affected the spatial variability of seismic motion (Kalogeras and Stavrakakis 2001, Gazetas and collaborators 2001). In addition, the earthquake din not present important ground failures (liquefaction, landslides, lateral spreading etc.) form the geotechnical point of view. The geotechnical and geological condition showed that: (a) the stiff soils encounterd within the Athens basin have amplified the peak ground acceleration relative to soft rocks. The average amplification performed at severely damaged areas was 40% and 46%, respectively, (b) the effect of stiff soils on the frequency content of seismic ground motions is less significant and can be overlooked (Bouckovalas *et al.* 2001).

The extent of the earthquake-striken areas derived from the database are mentioned in Table 2 and are correlated to the severity of the Macroseismic Intensity. The macroseismic intensity values have been estimated based on the three following sources (Eleftheriadou and Karabinis 2008c, 2011): 1. The information provided by the Geodynamic Institute of the National Observatory of Athens (NOA), 2. The results of a research programme referring to the estimated seismic intensity of the major area and 3. The existing isoseismal intensity maps which display significant similarity between them.

3. Development of the damage database

The observational data is obtained from post-earthquake surveys carried out after the 7th of September Parnitha's earthquake [$Mw = 5{,}9R$], a near field of city of Athens seismic event in an extended urban region of Greece. The damage data is derived from the inspections which have been conducted in several regions of Athens and is based on the instructions provided by EPPO (Earthquake Planning and Protection Organization) of Greece. The collected observational data came from different sources: (a) The Post-Earthquake Crisis Management Division of Axarnes region (including the regions of Filadelfeia – Axarnes –Ano Liosia). (b) The Post-Earthquake Crisis Management Division of Piraeus region (including the regions of Piraeus – down town of Athens – Peristeri – Eleusina). (c) The National Service for the Rehabilitation of Earthquake Victims. The initial damage dataset raised the enormous number of 535.152 reports of inspections and was developed after the first or the second phase of inspections including the "collapse" or "demolition" files, regardless of whether an inspection was mentioned twice in the previous files. The initial collected files from the different sources needed to be filtered (checking one-by-one the reports) and unified in a total database wherein each in situ inspection is reported once. After eliminating duplicate reports, the unified total database is derived referring to the extended urban region of Attica and consists of 296.919 unique inspections having avoided the overestimation of the damage level. It is essential to clarify that the pre-mentioned number refers to the number of inspections 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 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 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 (180.945) to the total number of buildings in the affected area (753.078) 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 (Kappos *et al.* 2002). The extent of damage can also be estimated from this information by making the reasonable assumption that in the earthquake-striken area, the damaged building stock has been thoroughly investigated and recorded and that almost all the non-surveyed buildings refer to nearly undamaged structures.

4. Data processing - results

A classification system to characterize the earthquake-exposed building stock and describe its damage is a necessary step for the vulnerability assessment. This requires the division of buildings into groups with similar seismic response after the occurrence of a probable earthquake. Problems associated with the parameters that influence structural vulnerability and, consequently, their seismic behaviour, remain largely unsolved internationally. Damage is predicted based on a specified building type, since both the structural system and the materials of construction are considered as the key factors in assessing the overall building performance. Parameters such as the design seismic code and the applied construction techniques at the time of construction, determine the detailing requirements and the available deformation capacity. They also express the seismic design practices of each period. Furthermore, it has been noticed that the existence of ground floor without infill panels (*pilotis*) or short columns, the existence of vertical or in-plan irregularities or the regular arrangements of masonry infills, influence significantly the development of earthquake damage. The number of storeys, which is related to the building height and the period of vibration used to be considered as one of the important factors that affect the building's seismic behaviour (National Technical Chamber of Greece 2001) but its role in the seismic response is nowadays under investigation (National Technical Chamber of Greece 2006).

Apart from the characteristics that affect the seismic response of a structure, the proposed classification system is also dependent on the available statistical database. The structural building types considered in the current paper are presented in Table 3. Unfortunately, the existence or not of ground floor without infill panels (*pilotis*) or other shape irregularities, which may influence significantly the seismic vulnerability, is not known. In the damage database, the buildings are divided into four groups according to structural systems: (1) Reinforced concrete buildings (RC) with moment resisting frames or dual system (frame + shear walls); (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

Table 3 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 period 1959-1985; RC2: during the period 1985-1995; and RC3 after 1995. The threshold of each period is identified with a change in Greek Seismic Codes. The mixed structures are further classified into MIX1, MIX2 and MIX3 using identical criteria as shown in Table 3. Buildings constructed before and after the introduction of the first Seismic Code are often treated similarly in Greece according to the National Technical Chamber of Greece (2006). Even if many buildings have been disregarded from the database due to the lack of information, such as the structural type or the date of construction, the presented here building stock still remains a wide statistical database.

The level of seismic design and detailing in Greece, could generally be discriminated in four subclasses, as follows: (1) *No Seismic Code* (or pre-seismic code: before 1959): R/C buildings with practical very low level of seismic design or no seismic design, and poor quality of detailing; (2) *Low Seismic Code (1959-1985: the 1st Seismic Code of 1959)*: R/C buildings with low level of seismic design (corresponding approximately to pre-1980 odes in Southern Europe); (3) *Moderate Seismic Code (1985-1995: the 1st Seismic Code of 1959 with the 1985 Supplement Clauses)*: R/C buildings with medium level of seismic design (corresponding approximately to post-1980 codes in S. Europe) and reasonable seismic detailing of R/C members; (4) *High Seismic Code (after 1995: NEAK/EAK2000,* similar to Eurocode 8): R/C buildings with adequate level of seismic design according to the new generation of seismic codes and ductile seismic detailing of R/C members including sufficient descriptions for detailing and anchorage.

After the time-consuming statistical elaboration and analysis of the database, important conclusions are drawn on the identification of structural system and materials, representative of the building stock of Southern Europe, the design seismic code and the height according to the provided available information of each parameter in the statistical data. The damage distribution is correlated with the above parameters in order to estimate their effect on the seismic response of structures. Damage Probability Matrices (DPMs) and Vulnerability Curves have been developed using the presented in the current paper damage statistics from the correlation of the seismic demand to the recorded level of damage (Eleftheriadou and Karabinis 2008b, 2011, Eleftheriadou 2009). This paper presents extensively the damage statistics from where the database was created for the development of Damage Probability Matrices. The pre-mentioned produced DPMs and Vulnerability Curves were derived from the created database by evaluating for each structural type and each intensity level, the relative frequency of the different damage states.

1. The distribution of buildings (180.427) according to the degree of damage is presented in Table 4. The 180.427 buildings of the database with damage characterization represents the 25,39% of the

Table 4 Distribution of buildings according to the degree of damage (180.427 buildings)

Damage state	Number of buildings (N_i)	N_i/N_{tot} (%)	N_i/753.078 (%)
Slight (Green)	114.755 (N_1)	63,60%	15,24%
Moderate (Yellow)	56.533 (N_2)	31,33%	7,50%
Extensive (Red)	6.423 (N_3)	3,56%	0,85%
Collapse (Black)	2.716 (N_4)	1,51%	0,36%
Total	180.427 (N_{tot})	100,00%	23,96%

total local population of buildings (710.556) regarding the earthquake-striken areas of Attica mentioned in the database from where the classified in structural types damaged buildings derived or 23,96% of the total local population of buildings (753.078) regarding the major area of Athens. Specifically: (a) the 2.716 structures which were characterised as *under demolition-collapse* (black) represents the 1,51% of the total damaged population of buildings (b) the 6.423 structures with extensive non-repairable damages (red) to the structural system represents the 3,56%, (c) the 56.533 structures with moderate (yellow) repairable also damages represents the 31,33% and (d) most of the structures (114.755) with light (green) repairable damages represents the 63,60%, respectively.

The information which was obtained from the damage statistics and is used in the current paper refers to the qualitative characterization of the recording of damage in post-earthquake surveys in Greece. The building label-damage calibration is based on instructions provided by EPPO (1984, 1997) using the method of Rapid Visual Screening (RVS) during the conduct of post-earthquake surveys in Greece. The last is based on a macroscopic inspection of the building in order to define whether the building's seismic resistance is adequate against future expected seismic forces, as follows: (a) *Green*: building without or with slight damage, or building without reduced seismic resistance; (b) *Yellow*: building with moderate damage and reduced seismic resistance; (c) *Red*: building with very heavy damage or partial collapse; and (d) *Collapse (black)*: building that has collapsed or is under demolition. In the collected data, there was no information about the repair costs or the physical description of damage.

The recent 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, 2007, ITSES-AUTh 2004). In the empirical seismic vulnerability assessment of these studies, the same calibration of damage has been used. In addition, in a proposed damage scale, a measurable calibration of seismic damage is presented according to the physical description and, as well, in terms of structural and economic damage index and is correlated with the previously mentioned qualitative description provided by EPPO and FEMA (Eleftheriadou and Karabinis 2008b, 2010, Eleftheriadou 2009).

At this point it is important to mention that the distribution of damage seems to change (they appear more buildings with moderate than light damage) in the Tables that follow in the effort of correlating seismic vulnerability to different factors (structural system, period of construction, etc.). The reason is because in the case of serious damages the survey was more accurate and thus data is included for the different parameters. In addition, in each parameter that it is analyzed the total number of the damaged buildings with available information differs and therefore the distributions are interesting mostly for a relative comparison.

2. The distribution of buildings (80.011) according to the structural system is presented in Table 5

Table 5 Distribution of buildings according to the structural system (80.011 buildings)

Structural system	Number of buildings (N_i)	N_i/N_{tot} (%)	N_i/753.078 (%)
RC (moment resisting frames or frame-wall)	41.051 (N_1)	51,31%	5,45%
MIX (Mixed buildings with vertical bearing structure by elements of both masonry and RC)	18.756 (N_2)	23,44%	2,49%
MAS (Masonry buildings with vertical elements of masonry and horizontal of RC, metal or wood)	14.580 (N_3)	18,22%	1,94%
OTH (Other buildings which typically are not included in the previous groups)	5.624 (N_4)	7,03%	0,75%
Total	80.011 ($N_{o\lambda}$)	100,00%	10,62%

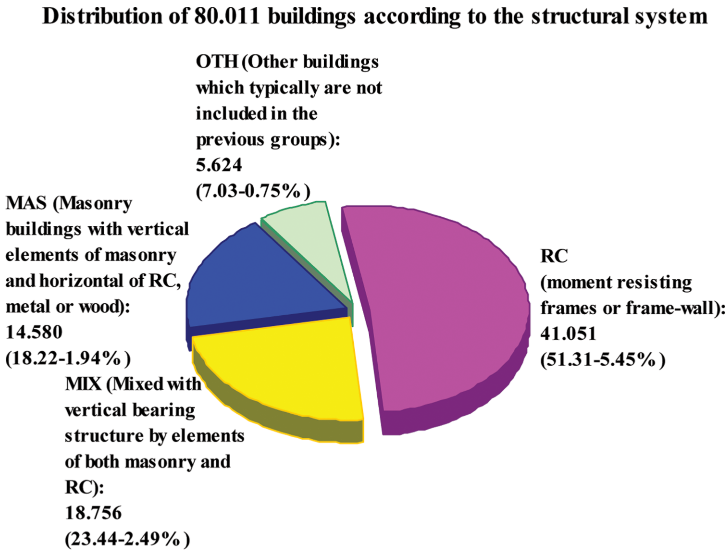

Fig. 2 Distribution of buildings according to the structural system (80.011 buildings)

and in Fig. 2. Among them it is noticed that: (a) the majority (41.051 RC buildings) refers to RC moment resisting frames or frame-wall and represents the 51,31% of the total number of buildings in the dataset having the information about the structural system, (b) many (18.756) refer to mixed buildings with vertical bearing structure with elements of both masonry and RC and represents the 23.44%, (c) many (14.580) refer to masonry buildings with vertical elements of masonry and horizontal of RC, metal or wood and represents the 18,22% and (d) 5.624 buildings (7,03%) refer to other buildings which typically are not included in the previous groups.

3. The distribution of buildings (74.734) according to the period of design (related to the respective seismic code) is presented in Table 6 (Fig. 3). Among the 74.734 buildings of the damage data with available information about the period of design it is concluded that: (a) the extensive majority (66.729 buildings) were constructed earlier than 1985 (Seismic Code of 1959 or without Seismic Code) and represents the 89,29% of the total number of buildings in the dataset having the information about the period of construction, (b) 5.989 buildings were constructed during the period 1985-1995 (Seismic Code of 1985) and represents the 8,01%, respectively and (c) 2.016

Table 6 Distribution of buildings according to the Seismic Code (74.734 buildings)

Period of design	Number of buildings (N_i)	N_i/N_{tot} (%)	Number of buildings N.S.S.G (K_i)	N_i/N.S.S.G (K_i) (%)
Earlier than 1985 (Seismic Code 1959)	66.729 (N_1)	89,29%	580.956 (K_1)	11,49%
1985 - 1995 (Seismic Code 1985)	5.989 (N_2)	8,01%	115.612 (K_2)	5,18%
After 1995 (Seismic Code 1995)	2.016 (N_3)	2,70%	56.510 (K_3)	3,57%
Total	74.734 (N_{tot})	100,00%	753.078 (K_{tot})	9,92%

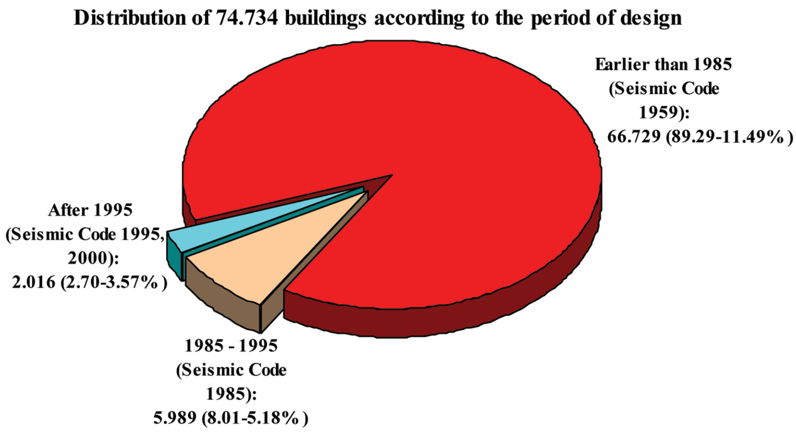

Fig. 3 Distribution of buildings according to the Seismic Code (74.734 buildings)

Table 7 Distribution of buildings according to the number of floors (164.391 buildings)

Number of floors	Number of buildings (N_i)	N_i/N_{tot} (%)	N_i/180.945 (%)	N_i/753.078 (%)
1	43.488 (N_1)	26,45%	24,03%	5,77%
2	48.967 (N_2)	29,79%	27,06%	6,50%
3	34.280 (N_3)	20,85%	18,94%	4,55%
4	14.096 (N_4)	8,57%	7,79%	1,87%
5	11.221(N_5)	6,83%	6,20%	1,49%
6	8.166 (N_6)	4,97%	4,51%	1,08%
7	2.710 (N_7)	1,65%	1,50%	0,36%
≥8	1.463 (N_8)	0,89%	0,81%	0,19%
Total	164.391(N_{tot})	100,00%	90,85%	21,83%

buildings were constructed after 1995 (Seismic Code of 1995) and represents the 2,70%. It is assumed for the damaged buildings without information regarding the period of construction, that most of them, refer to buildings constructed earlier than 1985. From the analysis of the sample it is concluded that the extensive majority of the existing buildings are constructed with Seismic Codes which are non-conforming to modern seismic detailing requirements and philosophy.

4. Table 7 presents the distribution of buildings (164.391) with available information about the

number of floors. The majority of the damage statistics (77,09%) refers to low-rise buildings with 1 to 3 floors.

5. The distribution of buildings (73.659) according to the period of design and the structural system is presented in Table 8 (Fig. 4). Among the damaged buildings (73.659) of the dataset with known the type of the structural system it is concluded that: (a) the majority refers to RC or mixed buildings with low (63,33%), moderate (6,92%) or high (2,32%) plasticity designed and constructed earlier than 1985, during the period 1985-1995 and after 1995, respectively, (b) many buildings (14.580) refer to masonry which represents the 19.79% of the total local population with available the information about the structural system and (c) 5.624 buildings (7,64%) belong to other structural system not included to the previous groups.

6. Table 9 presents the results from the correlation of the degree of damage vice the structural system for 79.840 buildings. Despite the fact that the dominant developed damage that was recorded belonged to a moderate and light level, many buildings developed heavy structural damages or were characterised as *under demolition.* In general, buildings of RC and MIX structural types exhibited better seismic performance in the earthquake compared to masonry buildings.

7. Table 10 presents the results from the correlation of the degree of damage vice the period of design for 74.607 buildings. It is evident from the correlation analysis that the buildings which were constructed according to older seismic codes developed heavier structural damage compared to

Table 8 Distribution of buildings according to the period of design and the structural system (73.659 buildings)

Structural type	Number of buildings (N_i)	N_i/N_{tot} (%)	Number of Buildings N.S.S.G (K_i)	N_i/N.S.S.G (K_i) (%)
RC1 & MIX1	46.645 (N_1)	63,33%	424.621 (K_1)	10,99%
RC2 & MIX2	5.099 (N_2)	6,92%	99.511 (K_2)	5,12%
RC3 & MIX3	1.711 (N_3)	2,32%	47.114 (K_3)	3,63%
MAS	14.580 (N_4)	19,79%	117.580 (K_4)	12,40%
OTH	5.624 (N_5)	7,64%	64.156 (K_5)	8,77%
Total	73.659 (N_{tot})	100,00%	752.982 (K_{tot})	9,78%

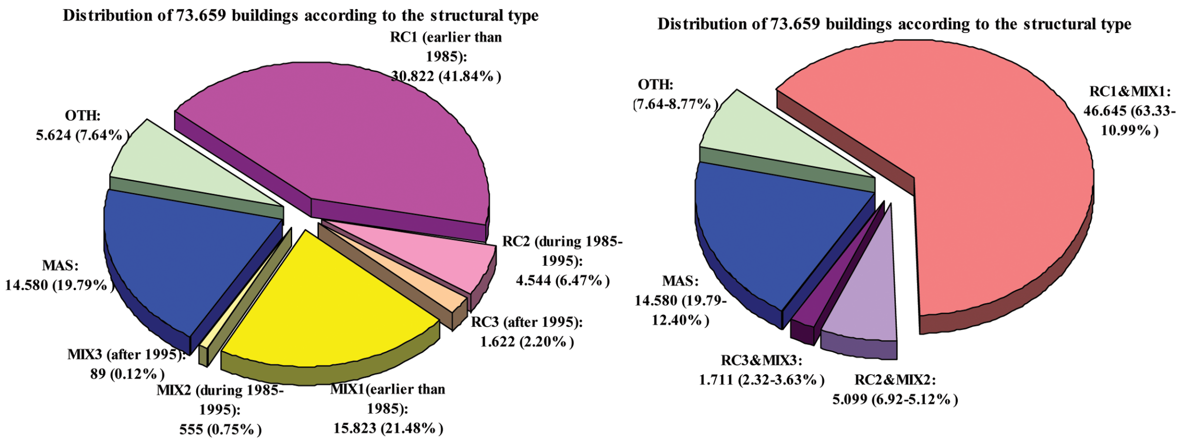

Fig. 4 Distribution of buildings according to the period of design and the structural system (73.659 buildings)

Table 9 Correlation for buildings of the degree of damage with the structural system (79.840 buildings)

Structural system	Damage state				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
RC (moment resisting frames or frame-wall)	14.079	25.201	1.182	479	40.941
	17,63%	31,56%	1,48%	0,60%	51,27% (N_i/N_{tot})
	7,78%	13,93%	0,65%	0,26%	22,62% (N_i/180.945)
	1,87%	3,35%	0,16%	0,06%	5,44% (N_i/753.078)
MIX (Mixed buildings with vertical bearing structure by elements of both masonry and RC)	5.058	12.179	1.024	472	18.733
	6,34%	15,25%	1,28%	0,59%	23,46% (N_i/N_{tot})
	2,79%	6,73%	0,57%	0,26%	22,62% (N_i/180.945)
	0,67%	1,61%	0,13%	0,06%	2,49% (N_i/753.078)
MAS (Masonry buildings with vertical elements of masonry and horizontal of RC, metal or wood)	2.991	10.030	1.062	472	14.555
	3,75%	12,56%	1,33%	0,59%	18,23% (N_i/N_{tot})
	1,65%	5,54%	0,59%	0,26%	8,04% (N_i/180.945)
	0,40%	1,33%	0,14%	0,06%	1,93% (N_i/753.078)
OTH (Other buildings which typically are not included in the previous groups)	658	3.401	1.094	458	5.611
	0,82%	4,26%	1,37%	0,58%	7,03% (N_i/N_{tot})
	0,36%	1,88%	0,61%	0,25%	3,10% (N_i/180.945)
	0,09%	0,45%	0,14	0,07	0,75% (N_i/753.078)
Total	22.786	50.810	4.330	1.914	79.840 (N_{tot})
	28,54%	63,64%	5,42%	2,40%	100,00%

Table 10 Correlation of the degree of damage vice the period of design (74.607 buildings)

Period of design	Damage state				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
Earlier than 1985	18.600	43.856	2.904	1.262	66.622
	24,93%	58,78%	3,89%	1,69%	89,30% (N_i/N_{tot})
	10,28%	24,24%	1,60%	0,70%	36,82%(N_i/180.945)
	2,47%	5,82%	0,39	0,17%	8,85% (N_i/753.078)
1985 – 1995	1.979	3.632	285	83	5.979
	2,65%	4,87%	0,38%	0,11%	8,01% (N_i/N_{tot})
	1,09%	2,00%	0,16%	0,05%	3,30%(N_i/180.945)
	0,26%	0,48	0,04%	0,01%	0,79% (N_i/753.078)
After 1995	779	1.134	71	22	2.006
	1,04%	1,52%	0,10%	0,03%	2,69% (N_i/N_{tot})
	0,43%	0,63%	0,04%	0,01%	1,11% (N_i/180.945)
	0,10%	0,15%	0,009%	0,003%	0,27% (N_i/753.078)
Total	21.358	48.622	3.260	1.367	74.607 (N_{tot})
	28,63%	65,17%	4,37%	1,83%	100,00%

those which are designed with modern regulations.

8. The correlation of the degree of damage vice the structural type for 73.537 buildings is presented in Table 11. The majority of the data refers to reinforced concrete with low ductility capacity and masonry buildings which developed moderate level of damage. On the contrary, among the RC buildings with high and moderate ductility capacity the developed damage was lighter.

9. The correlation of the degree of damage with the number of floors for 164.135 buildings is presented in Table 12. The role of height in the seismic response was considered important in the past whereas today its contribution is under investigation, especially for the normally infilled RC buildings. In general, the type of the buildings (height, seismic code, structural system) is strongly related to the region from where the damage was collected.

10. Finally, the correlation of the degree of damage vice the number of floors is presented in Tables 13 to 20 for the several structural types (30.149 RC1, 4.501 RC2, 1.591 RC3, 15.654 MIX1, 538 MIX2, 87 MIX3, 14.256 MAS, 5.240 OTH). From the analysis of the results it comes up that the moderate damage level was dominant in each examined structural type. In addition, it can be noticed a slight increase in the number of buildings, in every damage level, for the medium height buildings (2 to 5 floors).

Table 11 Correlation of the degree of damage vice the structural type (73.537 buildings)

Structural type	Damage state				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
RC1 (moment resisting frames or frame-wall-earlier than 1985)	10.556 14,35%	19.215 26,13%	692 0,94%	305 0,41%	30.768 41,84% (N_i/N_{tot})
RC2 (moment resisting frames or frame-wall-1985-1995)	1.609 2,19%	2.775 3,77%	101 0,14%	51 0,07%	4.536 6,17% (N_i/N_{tot})
RC3 (moment resisting frames or frame-wall-after 1995)	652 0,89%	910 1,24%	36 0,05%	17 0,02%	1.615 2,20% (N_i/N_{tot})
MIX1 (Mixed buildings with vertical bearing structure by elements of both masonry and RC - earlier than 1985)	3.941 5,36%	10.861 14,77%	646 0,88%	360 0,49%	15.808 21,50% (N_i/N_{tot})
MIX2 (Mixed buildings with vertical bearing structure by elements of both masonry and RC - 1985-1995)	125 0,17%	279 0,38%	138 0,19%	13 0,02%	555 0,75% (N_i/N_{tot})
MIX3 (Mixed buildings with vertical bearing structure by elements of both masonry and RC - after than 1995)	27 0,04%	53 0,07%	8 0,01%	1 0,00%	89 0,12% (N_i/N_{tot})
MAS (Masonry buildings with vertical elements of masonry and horizontal of RC, metal or wood)	2.991 4,07%	10.030 13,64%	1.062 1,44%	472 0,64%	14.555 19,80% (N_i/N_{tot})
OTH (Other buildings which typically are not included in the previous groups)	658 0,89%	3.401 4,62%	1.094 1,49%	458 0,62%	5.611 7,63% (N_i/N_{tot})
Total	20.559 27,96%	47.524 64,63%	3.777 5,14%	1.677 2,28%	73.537 (N_{tot}) 100,00%

Table 12 Correlation of the degree of damage vice the number of floors (164.135 buildings)

Number of floors	Damage state				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	22.496	16.913	2.778	1.208	43.395
	13,71%	10,30%	1,69%	0,74%	26,44% (N_i/N_{tot})
2	28.952	17.723	1.567	644	48.886
	17,64%	10,80%	0,95%	0,39%	29,78% (N_i/N_{tot})
3	21,230	12,014	728	266	34.238
	12,93%	7,32%	0,44%	0,16%	20,86% (N_i/N_{tot})
4	10.084	3.795	158	48	14.085
	6,14%	2,31%	0,10%	0,03%	8,58% (N_i/N_{tot})
5	9.315	1.826	47	18	11.206
	5,68%	1,11%	0,03%	0,01%	6,83% (N_i/N_{tot})
6	7.120	1.015	20	2	8.157
	4,34%	0,62%	0,01%	0,00%	4,97% (N_i/N_{tot})
7	2.270	427	9	0	2.706
	1,38%	0,26%	0,01%	0,00%	1,65% (N_i/N_{tot})
≥8	1.187	256	17	2	1.462
	0,72%	0,16%	0,01%	0,00%	0,89% (N_i/N_{tot})
Total	102.694	53.969	5.324	2.188	164.135 (N_{tot})
	62,54%	32,88%	3,24%	1,33%	100,00%

Table 13 Correlation of the degree of damage vice the number of floors for RC1 (30.149 buildings)

Number of floors	Damage state for RC1 structural type (moment resisting frames or frame-wall - earlier than 1985)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	1.017	1.948	110	52	3.127
	3,37%	6,46%	0,36%	0,17%	10,37% (N_i/N_{tot})
2	2.699	5.771	252	133	8.855
	8,95%	19,14%	0,84%	0,44%	29,37% (N_i/N_{tot})
3	2.745	6.248	227	94	9.314
	9,10%	20,73%	0,75%	0,31%	30,89% (N_i/N_{tot})
4	1.450	2.380	59	15	3.904
	4,81%	7,89%	0,20%	0,05%	12,95% (N_i/N_{tot})
5	1.044	1.196	15	7	2.262
	3,46%	3,97%	0,05%	0,02%	7,50% (N_i/N_{tot})
6	910	718	10	1	1.639
	3,02%	2,38%	0,03%	0,00%	5,44% (N_i/N_{tot})
7	356	309	3	0	668
	1,18%	1,02%	0,01%	0,00%	2,22% (N_i/N_{tot})
≥8	186	190	3	1	380
	0,62%	0,63%	0,01%	0,00%	1,26% (N_i/N_{tot})
Total	10.407	18.760	679	303	30.149 (N_{tot})
	34,52%	62,22%	2,25%	1,01%	100,00%

Table 14 Correlation of the degree of damage with the number of floors for RC2 (4.501 buildings)

Number of floors	Damage state for RC2 structural type (moment resisting frames or frame-wall – 1985 - 1995)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	146	256	5	6	
	3,24%	5,69%	0,11%	0,13%	
2	523	1.078	43	30	
	11,62%	23,95%	0,95%	0,67%	
3	408	800	37	12	
	9,06%	17,77%	0,82%	0,27%	
4	203	305	6	1	
	4,51%	6,78%	0,13%	0,02%	
5	181	210	5	2	
	4,02%	4,67%	0,11%	0,04%	
6	88	67	2	0	
	1,96%	1,49%	0,04%	0,00%	
7	22	28	1	0	
	0,49%	0,62%	0,02%	0,00%	
≥8	26	9	1	0	
	0,58%	0,20%	0,02%	0,00%	
Total	1.597	2.753	100	51	4.501
	35,24%	61,16%	2,22%	1,13%	100,00%

Table 15 Correlation of the degree of damage with the number of floors for RC3 (1.591 buildings)

Number of floors	Damage state for RC3 structural type (moment resisting frames or frame-wall – after 1995)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	57	101	3	2	
	3,58%	6,35%	0,19%	0,13%	
2	194	364	10	9	
	12,19%	22,88%	0,63%	0,57%	
3	127	206	15	3	
	7,98%	12,95%	0,94%	0,19%	
4	66	69	3	2	
	4,15%	4,34%	0,19%	0,13%	
5	99	81	5	0	
	6,22%	5,09%	0,31%	0,00%	
6	57	47	0	0	
	3,58%	2,95%	0,00%	0,00%	
7	25	27	0	0	
	1,57%	1,70%	0,00%	0,00%	
≥8	14	5	0	0	
	0,88%	0,31%	0,00%	0,00%	
Total	639	900	36	16	1.591
	40,16%	56,57%	2,26%	1,01%	100,00%

Table 16 Correlation of the degree of damage with the number of floors for MIX1 (15.654 buildings)

Number of floors	Damage state for MIX1 structural type (mixed buildings with vertical bearing structure by elements of both masonry and RC – earlier than 1985)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	1.145	3.155	235	140	
	7,31%	20,15%	1,5%	0,89%	
2	1.687	4.635	268	141	
	10,77%	29,61%	1,71%	0,90%	
3	770	2.228	111	60	
	4,92%	14,23%	0,71%	0,38%	
4	188	516	15	14	
	1,20%	3,30%	0,10%	0,09%	
5	49	129	1	2	
	0,31%	0,82%	0,01%	0,01%	
6	40	45	2	0	
	0,26%	0,29%	0,01%	0,00%	
7	16	23	0	0	
	0,10%	0,15%	0,00%	0,00%	
≥8	11	22	5	1	
	0,07%	0,14%	0,03%	0,01%	
Total	3.906	10.753	637	358	15.654
	24,95%	68,69%	4,07%	2,29%	100,00%

Table 17 Correlation of the degree of damage with the number of floors for MIX2 (538 buildings)

Number of floors	Damage state for MIX2 structural type (mixed buildings with vertical bearing structure by elements of both masonry and RC – 1985-1995)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	37	88	13	3	
	6,88%	16,36%	2,42%	0,56%	
2	45	111	42	3	
	8,36%	20,63%	7,81%	0,56%	
3	24	52	29	4	
	4,46%	9,67%	5,39%	0,74%	
4	8	10	25	1	
	1,49%	1,86%	4,65%	0,19%	
5	7	8	9	2	
	1,30%	1,49%	1,67%	0,37%	
6	1	5	2	0	
	0,19%	0,93%	0,37%	0,00%	
7	0	1	3	0	
	0,00%	0,19%	0,56%	0,00%	
≥8	1	0	4	0	
	0,19%	0,00%	0,76%	0,00%	
Total	123	275	127	13	538
	22,86%	51,12%	23,61%	2,42%	100,00%

Table 18 Correlation of the degree of damage with the number of floors for MIX3 (87 buildings)

Number of floors	Damage state for MIX3 structural type (mixed buildings with vertical bearing structure by elements of both masonry and RC – after 1995)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	9	18	2	0	
	10,47%	20,93%	2,33%	0,00%	
2	11	18	5	1	
	12,79%	20,93%	5,81%	1,16%	
3	4	10	1	0	
	4,65%	11,63%	0%	0,00%	
4	1	3	0	0	
	1,16%	3,49%	0,00%	0,00%	
5	2	0	0	0	
	2,33%	0,00%	0,00%	0,00%	
6	0	0	0	0	
	0,00%	0,00%	0,00%	0,00%	
7	0	1	0	0	
	0,00%	1,16%	0,00%	0,00%	
≥8	0	1	0	0	
	0,00%	1,16%	0,00%	0,00%	
Total	27	51	7	1	87
	31,40%	59,30%	8,14%	1,16%	100,00%

Table 19 Correlation of the degree of damage with the number of floors for MAS (14.256 buildings)

Number of floors	Damage state for MAS structural type (masonry buildings with vertical elements of masonry and horizontal of RC, metal or wood)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	2.058	6.720	696	340	
	14,44%	47,14%	4,88%	2,38%	
2	703	2.489	253	99	
	4,93%	17,46%	1,77%	0,69%	
3	142	469	60	18	
	1,00%	3,29%	0,42%	0,13%	
4	24	78	9	3	
	0,17%	0,55%	0,06%	0,02%	
5	14	30	1	1	
	0,10%	0,21%	0,01%	0,01%	
6	10	24	1	0	
	0,07%	0,17%	0,01%	0,00%	
7	3	5	2	0	
	0,02%	0,04%	0,01%	0,00%	
≥8	2	1	1	0	
	0,01%	0,01%	0,01%	0,00%	
Total	2.956	9.816	1.023	461	14.256
	20,74%	68,86%	7,18%	3,23%	100,00%

Table 20 Correlation of the degree of damage with the number of floors for OTH (5.240 buildings)

Number of floors	Damage state for OTH structural type (other buildings which typically are not included in the previous groups)				
	Slight (Green)	Moderate (Yellow)	Extensive (Red)	Collapse (Black)	
1	490	2.380	769	339	
	9,35%	45,42%	14,68%	6,47%	
2	99	597	176	73	
	1,89%	11,39%	3,36%	1,39%	
3	23	137	31	10	
	0,44%	2,61%	0,59%	0,19%	
4	14	20	4	4	
	0,27%	0,38%	0,08%	0,08%	
5	2	6	0	1	
	0,04%	0,11%	0,00%	0,02%	
6	0	7	1	0	
	0,00%	0,13%	0,02%	0,00%	
7	0	1	0	0	
	0,00%	0,02%	0,00%	0,00%	
≥8	2	2	0	0	
	0,04%	0,04%	0,00%	0,00%	
Total	634	3.174	1.002	430	5.240
	12,10%	60,57%	19,12%	8,21%	100,00%

The structural damage can be considered the greatest cause of life and monetary loss in most earthquakes and can be used to assess the performance of buildings. In each database, this is described in terms of either damage state or percentage of loss. Due to the different parameters that influence the recording of damage (building types, seismic design codes, performance levels, etc.), it cannot be easily compared nor is it easy to combine and compare damage data. Comparisons of the recording damage have been presented in the literature (Rossetto and Elnashai 2003, Rota *et al.* 2006, Sarabandi *et al.* 2003, Eleftheriadou *et al.* 2008b, 2010, Eleftheriadou 2009). The description of damage of every performance level is often mainly based on ATC-13 (1985). This is also the case for the damage calibration regarding the economic damage index in Greece (Kappos *et al.* 2002, National Technical Chamber of Greece 2006) and in several other vulnerability studies (Kappos 2007, Tesfamariam and Saatcioglu 2008).

Finally, loss assessment (in monetary terms) due to seismic damage in an urban area struck by an earthquake needs both the reliable estimation of seismic hazard and vulnerability assessment. The seismic damage was sampling represented in the municipality of Ano Liosia, the meizoseimal area where most heavy damages were recorded after the 7th of September 1999 Parnitha's earthquake (Fig. 5). The information was collected from the created database and included for each damaged building data regarding the address, the structural system, the year of construction (therefore the seismic code), the characterization and level of damage (1st or/and 2nd level of inspection), the number of stories. From the typical floor area and the number of stories is also calculated the volume of the building. The use of the repair cost provided from the Departments for Seismic

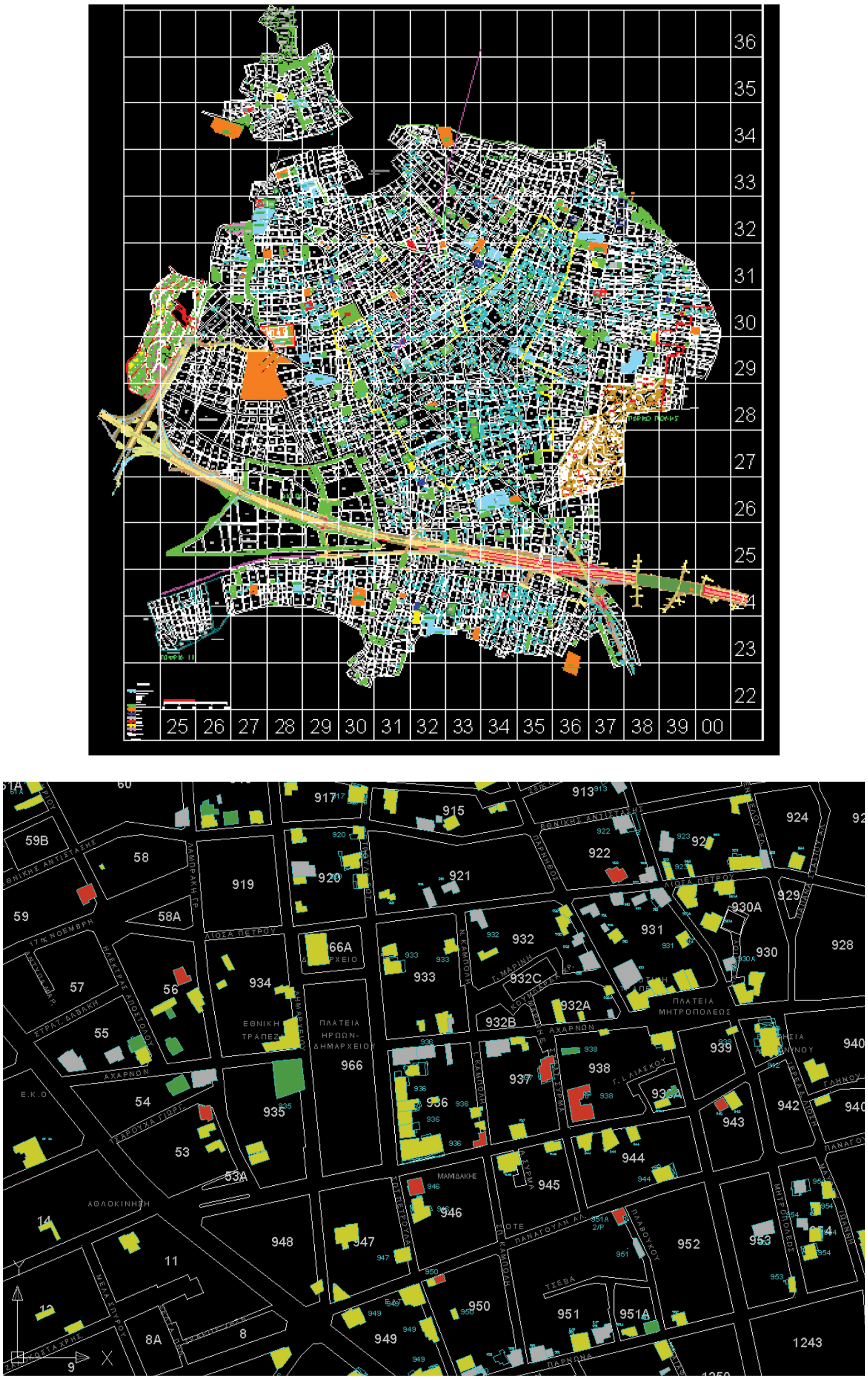

Fig. 5 Spatial distribution of seismic damage in the meizoseismal area (Municipality of Ano Liosia)

Restoration (TAS) leads to an estimation of the total statistical cost of the specific area or the whole region of Attica which is beyond of the scope of the present paper.

6. Conclusions

The present paper focuses on the empirical seismic vulnerability assessment of typical building types, representative of Southern Europe. A damage database with 180.945 buildings has been created from the processing of the observational data after the occurrence of a medium to large magnitude near field Athens earthquake (7-9-1999). Correlation analysis has been conducted between the developed structural damage and several factors which contribute to the seismic response of the buildings.

Based on geological, tectonic and morphological characteristics of the affected area, the recorded damage after the 7^{th} of September 1999 earthquake displayed significant differentiation from place to place, as well as a peculiar geographic distribution reflecting the destructive combination of the source directivity and the site effect.

From the analysis results, it is concluded that: (1) The majority of buildings sustained light and moderate damage. However, it was recorded a number of severe structural damage and some buildings collapsed, partially or totally. (2) The typical existing building stock mainly consists of reinforced concrete moment resisting frames or dual systems of frame-shear walls. (3) The extensive majority (89,29% of the total number of buildings in the dataset) of the buildings were built according to the 1959 Seismic Code (without ductility provisions) with significantly lower seismic forces than those experienced during the earthquake, or in the worst case with no code at all and were of poor construction, without conforming even to the minimum requirements (of the 1^{st} Greek Seismic Code of 1959) and had great disparity from the modern seismic detailing requirements and philosophy. The last, combined with the disparity in the intensity severity of shaking and construction deficiencies, could explain the severity and extent of damage in the meizoseismal area (Ano Liosia, Aharnes, Metamorfosi, Philadelphia, Thrakomakedones). (4) The majority of the damage statistics (77,09%) referred to low-rise buildings with 1 to 3 floors. (5) In general, buildings of RC and MIX structural types exhibited better seismic performance in the earthquake compared to masonry buildings. The overall behaviour of RC structures was satisfactory. (6) The buildings which were constructed according to older seismic codes developed heavier structural damage compared to those which are designed with modern regulations. (7) The majority of the data referred to reinforced concrete with low plasticity and masonry buildings which developed moderate level of damage. On the contrary, among the RC buildings with high and moderate plasticity the developed damage was lighter. (8) Once again, Parnitha's earthquake revealed typical building failures and design/construction deficiencies affecting the seismic response of structures (shear failures of short columns, soft ground stories - *pilotis*, lack of adequate transverse reinforcement - *stirrups*, failures in joints, inadequate shear-walls, poor quality of concrete, pounding with adjacent buildings, irregularities etc.).

The seismic behaviour of the structures during an earthquake represents an experiment of a physical scale (1:1) and constitutes the most objective examination of the sufficiency of seismic codes and construction techniques. However, the reliable estimation of buildings response depends on the used method for the recording of seismic damage which may vary in detail (approximate, analytical, etc.) and extent (numerous buildings, group of buildings or a single structure). The presented here vulnerability assessment based on a statistical analysis of damage data has the advantage of representing, according to up to the present writers knowledge, the largest in volume database in Greece and one of the biggest worldwide. Important conclusions are drawn on the parameters that influence the seismic response based on the wide homogeneous database which adds to the reliability of the collected information.

References

Andrikopoulou, K.P. (1989), "Damage assessment from the earthquakes of Kalamata on 1986 – Correlation of dαmage distribution with soil conditions in Kalamata: national report", *Bull. Int. Inst. Seismol. Earthq. Eng.*, **23**, 169-188.

ATC-13 (1985), *Earthquake Damage Evaluation Data for California*, Redwood City, CA.

Bouckovalas, G.D. and Kouretzis, G.P. (2001), "Stiff soil amplification effects in the 7 September 1999 Athens (Greece) earthquake", *Soil Dyn. Earthq. Eng.*, **21**(8), 671-687.

Carreño, M.L., Cardona, O.D. and Barbat, A.H. (2004), "New techniques applied to post earthquake assessment of buildings", *Intersection/Intersectii*, **1**(9), 12-22.

Dolce, M., Kappos, A., Masi, A., Penelis, G. and Vona, M. (2006) "Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies", *Eng. Struct.*, **28**(3), 357-371.

Dolce, M., Masi, A., Marino, M. and Vona, M. (2003), "Earthquake damage scenarios of the building stock of Potenza (Southern Italy) including site effects", *Bull. Earthq. Eng.*, *Kluwer Academic Publishers,* **1**(1), 115-140.

D' Ayala, D., Spence, R., Oliveira, C. and Pomonis, A. (1997), "Earthquake loss estimation for Europe's historic town centres", *Earthq. Spectra*, **13**(4), 773-793.

Eleftheriadou, A.K. (2009), "Contribution to the seismic vulnerability assessment of reinforced concrete structures" (in Greek), Ph.D. Thesis, Civil Engineering Dept, Democritus University of Thrace, Greece.

Eleftheriadou, A.K. and Karabinis, A.I. (2008a), "Empirical seismic vulnerability evaluation based on earthquake damage data", *Proceedings of the International Conference on Earthquake Engineering and Disaster Mitigation 2008,* paper no.**ICEED08-159**, Jakarta, Indonesia.

Eleftheriadou, A.K. and Karabinis, A.I. (2008b), "Damage probability matrices derived from earthquake statistical data", *Proceedings of the 14th World Conference on Earthquake Engineering,* paper no.**07-0201**, Beijing, China.

Eleftheriadou, A.K. and Karabinis, A.I. (2008c), "Seismic vulnerability assessment with damage probability matrices" (in Greek), *Proceedings of the 3rd Greek Conference on Earthquake Engineering and Technical Seismology*, paper no.**2108**, Athens, Greece.

Eleftheriadou, A.K. and Karabinis, A.I. (2010), "Seismic damage scales in reinforced concrete structures" (in Greek), *Technika Chronika, Scientific Journal of the Technical Chamber of Greece,* no.**3**/2010.

Eleftheriadou, A.K. and Karabinis, A.I. (2011), "Development of damage probability matrices based on Greek earthquake damage data," *Earthq. Eng. Eng. Vib.*, **10**(1), 129-141.

Faccioli, E., Pessina, V., Calvi, G.M. and Borzi, B. (1999), "A study on damage scenarios for residential buildings in Catania city", *J. Seismol.*, **3**(3), 327-343.

FEMA 273. (1997), "NEHRP Guidelines for the seismic rehabilitation of buildings", *Federal Emergency Management Agency*, Washington, DC.

Foltz, R. (2004), "Estimating seismic damage and repair costs", *MAE Center Project CM-4*, The Citadel, Texas A&M, Advisor Dr. Mary Beth Hueste.

Gazetas, G. and Collaborators (2001), "Computational and experimental assessment of strong motion within the meizoseismal area of Parnitha, 7-9-99, earthquake (in Greek)" (in Greek), *Technical Report*, *Earthquake Planning and Protection Organization,* Athens, 1-207.

Ghobarah, A. (2004), "On drift limits associated with different damage levels", *Proceedings of International Workshop on Performance-Based Seismic Design,* Department of Civil Engineering, McMaster University, Bled, Slovenia.

HAZUS[R]99 (SR2) (1999), "Earthquake loss estimation methodology", Advanced Engineering Building Module, Technical and User's Manual, *Federal Emergency Management Agency (FEMA), National Institute of Building Sciences*, Washington, D.C.

Hutchings, L., Ioannidou, E., Foxall, W., Voulgaris, N., Savy, J., Kalogeras, I., Scognamiglio, L. and Stavrakakis, G., (2007), "A physically based strong ground-motion prediction methodology; application to PSHA and the 1999 *M*w = 6.0 Athens earthquake", *Geophys. J. Int.*, **168**(2), 659-680.

ITSAK-AUTH (2004), "Athens earthquake: assessment of vulnerability in the disaster area and correlation to the real distribution of buildings damage after the earthquake", (in Greek), *Research Program*, *Institute of Engineering Seismology and Earthquake Engineering (ITSAK) - Earthquake Planning and Protection Organization (EPPO),* Thessaloniki, Greece. (In Greek).

Kalogeras, I.S. and Stavrakakis, G.N. (2001), "The Athens, Greece September 7th, 1999 earthquake: strong motion data processing (7/9/1999- 31/3/2000)", *National Observatory of Athens, Geodynamic Institute*, publ. **14**, cd-rom with user's manual.

Kappos A.J., Stylianidis K.C. and Pitilakis K. (1998), "Development of seismic risk scenarios based on a hybrid method of vulnerability assessment", *Journal of Natural Hazards*, **17**(2), 177-192.

Kappos, A.J. (2007), "Seismic vulnerability and risk assessment of urban habitat in Southern European cities", *Proceedings of the Urban Habitat Constructions under Catastrophic Events Workshop,* (COST C26), 115-129, Prague.

Kappos, A.J., Lekidis, V., Panagopoulos, G., Sous, I., Theodulidis, N., Karakostas, Ch., Anastasiadis, T., Salonikios, T. and Margaris, B. (2007), "Analytical estimation of economic loss for buildings in the area struck by the 1999 Athens earthquake and comparison with statistical repair costs", *Earthq. Spectra,* **23**(2), 333-355.

Kappos, A.J., Pitilakis, K., Morfidis, K. and Hatzinikolaou, N. (2002), "Vulnerability and risk study of Volos (Greece) metropolitan area", *Proceedings of the 12th ECEE*, **74**, London, UK.

Karabinis, A.I. and Baltzopoulou, A.D. (2006), "Correlation of damage factor and repairing cost in structures damaged by the 7th - 9 – 1999 Athens earthquake" (in Greek), *Proceedings of the 15th Greek Conference on Concrete*, Alexandroupoli, **B3**, 294-304.

Karabinis, A.I. and Eleftheriadou, A.K. (2007), "Vulnerability assessment derived from earthquake damage data", *Proceedings of the ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, **1264**. Rethymno, Crete, Greece.

Karantoni, F.V. and Fardis, M.N. (2004), "Damage to reinforced concrete buildings due to the aegion (gr) 1995 earthquake", *International Symposium Durability and Maintenance of Concrete Structures,* Dubrovnik, Croatia, 249-256.

Katsikas, A., Theodorakis, S., Thoma, T.H. and Panagiotopoulou, D. (2006), "ARISTION/Part6.2.b. – Damage data from the repair files", (in Greek), *Earthquake Planning and Protection Organization,* Athens, Greece.

Lagomarsino, S. and Giovinazzi, S. (2006), "Macroseismic and mechanical model for the vulnerability and damage assessment of current buildings", *Bull. Earthq. Eng.*, **4**(4), 415-443.

Lekkas, E. (2001), "The Athens earthquake (7 September 1999): intensity distribution and controlling factors", *Eng. Geol.*, **59**(3-4), 297-311.

National Technical Chamber of Greece (2001), *Vulnerability Assessment of Buildings* (in Greek), National programme for earthquake management of existing buildings, Final Report, Technical Team No.I.2, Athens, Greece.

National Technical Chamber of Greece (2006), *Pre-Earthquake Reinforcement of Existing Buildings* (in Greek), National programme for earthquake management of existing buildings, Athens, Greece.

Panagopoulos, G. and Kappos, A.J. (2009), "Development of a unified seismic damage database for buildings from Greek earthquakes and utilization for the derivation of fragility curves", (in Greek), *Proceedings of 16th Concrete Conference,* Pafos, Cyprus.

Papadimitriou, P., Voulgaris, N., Kassaras, I.G., Kaviris, G., Delibasis, N. and Makropoulos, K. (2002), "The *Mw* = 6.0, 7 September 1999 Athens Earthquake", *Natural Hazards, Kluwer Academic Publishers*, **27**(1-2), 15-33.

Penelis, G.G., Sarigiannis, D., Stavrakakis, E. and Stylianidis, K.C. (1989) "A statistical evaluation of damage to buildings in the Thessaloniki, Greece, earthquake of June, 20, 1978", *Proceedings of 9th WCEE,* Tokyo-

Kyoto, Japan, **VII**, 187-192.
Rossetto, T. and Elnashai, A. (2003), "Derivation of vulnerability functions for European-type RC structures based on observational data", *J. Eng. Struct.*, **25**(10), 1241-1263.
Rota, M., Penna, A. and Strobbia, C.L. (2008), "Processing Italian damage data to derive typological fragility curves", *Soil Dyn. Earthq. Eng*., **28**(10-11), 933-947.
Roumelioti, R., Kiratzi, A. and Theodulidis, N. (2004), "Stochastic strong ground-motion simulation of the 7 september 1999Athens (Greece) earthquake", *B. Seismol. Soc. Am.*, **94**(3), 1036-1052.
Sarabandi, P., Pachakis, D., King, S. and Kiremidjian, A. (2003), "Development of empirical building performance functions data from past earthquakes", *Proceedings* of *ICASP-9*, 629-635.
Schenková, Z., Schenk, V., Kalogeras, I., Pichl, R., Kottnauer, P., Papatsimba, C. and Panopoulou, G. (2007), "Isoseismal maps drawing by the Kriging method", *Journal of Seismology*, Springer Netherlands, **11**(1), 121-129.
SEAOC 1995 (1995), *Vision 2000 - A framework for performance based design, Volumes I, II, III*. Structural Engineers Association of California, Vision 2000 Committee. Sacramento, California.
Tesfamariam, S. and Saatcioglu, M. (2008), "Risk-based seismic evaluation of reinforced concrete buildings", *Earthq. Spectra,* Earthquake Engineering Research Institute, **24**(3), 795-821.
Vlahos, I. and Vlahos, S. (2008), "Correlation of economic losses due to earthquake with the structural characteristics of structures" (in Greek), *Proceedings of the 3rd Greek Conference on Earthquake Engineering and Technical Seismology*, Athens, Greece.

SA