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Seismic vulnerability assessment for buildings in Greece based on observed damage data sets

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ABSTRACT A database of observed damage to Greek reinforced concrete (RC) and unreinforced masonry (URM) buildings is compiled from post-earthquake damage surveys carried-out by government authorities and university researchers after four different moderate magnitude shallow crustal earthquakes that took place in the period 1986 to 2003. It contains data sets on 28,747 buildings. The data sets are homogenized by the development of damage scales specific to RC and URM buildings respectively. The European Macroseismic Scale (EMS-98) of intensity is used as the common descriptor of ground motion severity. The database allowed the derivation of observed damage-based vulnerability curves to be fitted to the data and describe the relative vulnerability of 10 structural types commonly found in Greece, including the expected performance of RC buildings according to four different periods of construction, the number of floors and the existence or not of soft-storey at ground floor level. This vulnerability analysis covers most of the existing buildings in Greece's zone II of the current earthquake code (introduced in 2004) and about half of all the existing buildings in the country and is valid for the EMS-98 intensity range of VI to IX degrees. We also report on the economic cost factors associated with the repair of Greek RC buildings by damage grade and the factors that influence the scatter in the costs of repair, thus allowing earthquake loss assessment and mitigation scenarios to be implemented.

Key words: observed earthquake damage, empirical seismic vulnerability assessment, earthquake damage surveys, EMS intensity scale, Greece, SEAHELLARC.

1. Introduction

In the past three decades several earthquakes have caused damage in various parts of Greece and a significant effort has been made by the authorities to assess and record their effects on buildings. Structural vulnerability assessment based on observed damage was first proposed in the form of damage probability matrices (DPMs) by Whitman *et al.* (1973) with the modified Mercalli intensity scale as its common denominator. DPMs express, in a discrete form, the conditional probability of obtaining a damage level (e.g., collapse or serious structural damage, etc.), due to a ground motion of certain intensity. Later on vulnerability (fragility) curves were derived from analysis of various observed damage data sets obtained after damaging earthquakes, expressing the probability of exceeding a given damage level at distinct levels of ground motion severity [described by the peak ground acceleration (*PGA*) or other ground motion parameters]. For buildings in Europe and elsewhere the studies of Spence *et al.* (1992), Rossetto and Elnashai (2003), Lagomarsino and Giovinazzi (2006), Colombi *et al.* (2008) and Rota *et al.* (2008) belong in this category. For Greek buildings, fragility curves have also been derived from hybrid methodologies (Kappos *et al*., 2006; Kappos and Panagopoulos, 2010), based on a combination of real observed damage data and analytical models. In addition, intensity-based DPM's were proposed for Greek buildings by Kappos *et al.* (2002) and Eleftheriadou and Karabinis (2008), the latter based on the post-earthquake damage surveys of the 1999 earthquake near Athens. Recently, Karababa and Pomonis (2011) have proposed a new set of empirical fragility curves resulting from the 2003 Lefkas Island earthquake observed damage data.

There are several advantages but also limitations when using observed damage data to study the vulnerability of the existing building stock in a region. Although post-earthquake damage surveys have been developed primarily for assessing the safety and usability of damaged buildings, they also provide a wealth of information that can be used towards understanding vulnerability. Furthermore, in most regions existing buildings are a mix of old non-engineered buildings, buildings that have been constructed prior to the introduction of earthquake codes as well as engineered buildings built during periods when different earthquake codes were in application. Analytical models for such a wealth of structural types are hard to construct and validate. It is therefore important that observed damage data are collected and further utilized to the benefit of society. Finally a further useful aspect of utilizing and analyzing observed damage data sets is that they enable us to carry out checks and validations of vulnerability assessments based on purely analytical methods (Colombi *et al.*, 2008).

On the other hand, however, it is imperative that the observed damage data be extensive, covering a wide range of existing building types that have been subjected to a wide range of ground motion severities and that the damage surveys be complete (i.e., to cover all the buildings and all the damage states including the buildings that were not damaged within an affected study zone). This usually requires for a compilation to be made of observed damage data sets in a wide region and/or across several events so that the necessary breadth of information is captured. For Greece in particular it is also important that damage data sets contain sufficient information on the performance of unreinforced masonry (URM) buildings, as well as reinforced concrete (RC) buildings built during the period of application of the successive earthquake codes (in the case of Greece 1959, 1985, 1995 and 2004 are the benchmark years of introduction of successive earthquake codes).

In the present study whilst keeping all these limitations in mind we develop a Greek observed damage database based on 4 earthquakes that took place in the period 1986-2003 (the September 13, 1986 Kalamata earthquake; the March 26, 1993 Pyrgos earthquake; the June 15, 1995 Aegion earthquake and the August 14, 2003 Lefkas Island earthquake). The four earthquakes had surface-wave magnitude in the range of 5.5 to 6.4. The first three of the events occurred within the space of 11 years in the region of Peloponnese and the damage survey procedures used were quite similar. Also all three affected towns were within zone II of the 1959, 1984 and 2004 earthquake codes of Greece and in zone III of the code that was in use in the period 1995-2003 (which unlike the other 3 codes contained four zones). Using this database we were able to derive

EMS-intensity based vulnerability functions for several low-rise (1 to 3 floors) and medium-rise (4 to 7 floors) building types commonly found in Greece.

Additional damage data sets exist for other recent earthquakes in Greece [June 20, 1978 Thessaloniki (Penelis *et al.*, 1989); July 26 and August 6, 1996 Konitsa (Dandoulaki *et al.,* 1998; Dandoulaki, 2008) and September 7, 1999 Athens (Eleftheriadou and Karabinis, 2008)] but have not been used in the present study, as they did not contain the necessary level of detail to allow differentiation of the RC structures by age, height and the existence or absence of soft storey at ground floor level.

2. Earthquake damage characterization and homogenization for Greek building types

Through the analysis of observed damage data sets, the heterogeneity both of the post-earthquake damage surveys and of the damage data from which vulnerability curves are derived (Rota *et al.*, 2008; Gaspari, 2009) became apparent. Intuitively, data should be as much as possible homogeneous both in time and space, since significant variations of construction techniques may occur during time and from place to place, and this may compromise the homogeneity of building classes. Furthermore, damage surveys across a long period of time are usually performed using different forms and procedures. To address this limitation, we tried to correlate the damage degrees of the varied damage scales used for each damage survey so that a uniform damage scale was formed for each structural type.

In Greece, earthquake disaster response and reconstruction was drastically reviewed after the experiences gained in the aftermath of the June 1978 Thessaloniki and the February-March 1981 Corinth Bay earthquakes. The Earthquake Planning and Protection Organization of Greece (EPPO), was established in 1983 with the task to deal with matters related to earthquake safety and to coordinate all private and public actions for earthquake protection. EPPO formally introduced the first post-earthquake building safety assessment (usability) procedures in Greece in 1984. Three categories of safety-usability and the corresponding posting (tagging) scheme (“green” for usable; “yellow” for temporarily unusable and “red” for unusable/dangerous) and six categories of damage, were formed. There were four grades of damage in structural elements (light, significant, serious and heavy damage) and an explicit description of the damage in each grade and structural element was issued, aiming to a uniform damage grading. A field manual was issued and distributed to engineers, administrators and agencies involved in post-earthquake inspection of buildings (EPPO, 1984).

In 1997, EPPO proposed a new post-earthquake building inspection procedure for the first level quick response damage and usability assessments (which largely maintained but simplified the 1984 inspection form) while keeping the three-colour building safety categorization unchanged. For the more detailed second degree inspections (taking place for buildings that have the “yellow” or “red” damage grade) the 1984 EPPO guidelines remain in use (EPPO, 1997). Details of these documents are also presented by Dandoulaki *et al.* (1998).

2.1. Damage scale for RC buildings

For the RC buildings, we had damage data sets from three of the four events (the 1993 Pyrgos

Table 1 - Correlation between the damage scales used in three post-earthquake surveys of RC buildings. The tagging colour is used.

Damage description		
Kalamata (1986)	Aegion (1995)	Lefkas (2003)
Undamaged or slight non-structural damage	Undamaged or slight non-structural damage	No damage
		Slight non-structural damage
Light (moderate) structural damage	Moderate to serious structural damage	Moderate to serious structural damage
Heavy structural damage	Very heavy structural damage - collapse	Very heavy structural damage - collapse
Very heavy structural damage (incl. partial and total collapse) that will be demolished		

earthquake caused only limited damage to RC buildings). As seen in Table 1, RC buildings in the 1986 Kalamata, 1995 Aegion and 2003 Lefkas earthquakes (Argyrakis *et al.*, 1987; Fardis *et al.*, 1997; Karababa, 2007; Karababa and Pomonis, 2011) were assigned the three EPPO usability classes, with the exception of Kalamata, where an additional fourth class ("purple") was used for the buildings that collapsed or were heavily damaged and deemed irreparable.

In this analysis the "purple" buildings of Kalamata that did not collapse (39 out 44 RC buildings) were included in the "red" damage grade. In Greece the "red-tag" is given to buildings with the worst damage that are deemed unsafe for occupation and will need a second-degree damage and safety assessment. After the second inspection a building that continues to be classified as "red" is usually issued with a "protocol for demolition" as repair is deemed not feasible or uneconomical.

Furthermore, in order for the damage grades to be homogeneous across all 3 event-surveys, for the Kalamata data we assumed that the buildings with "red-tag" had actually suffered damage similar to those assigned the "yellow-tag" in Aegion and Lefkas Island. This is because in Kalamata due to strong aftershocks taking place in the days after the main shock a conservative approach was deemed necessary for the safety of the citizens which resulted in 893 RC buildings assigned the "red tag" (i.e., entry is absolutely prohibited) in the first-degree inspections. Later-on when the more detailed second-degree damage and safety assessment took place the overwhelming majority of these buildings were re-assigned with "yellow tag" (personal communication with Costas Ioannides of the Greek Earthquake Rehabilitation Service). This is also corroborated by the fact that the number of RC buildings that were eventually issued with a "protocol for demolition" in Kalamata was not so great. It is possible that some under-estimation of the damage severity in Kalamata may be taking place due to this assumption (since in this way we assume that 52.4% of the RC buildings in Kalamata were yellow-tagged instead of 31.2% in the original 1986 first-degree inspections).

One other problem lies in the fact that buildings that may have not been damaged were not separately recorded in the case of Kalamata and Aegion but were grouped together with the buildings that had light damage to the infill panels. Although, in the case of both towns it could

Table 2 – Proposed damage scale of RC buildings (EPPO+).

Damage Scale	**Damage Description**
White (D0)	No damage.
Green (D1)	Fine cracks to the infill walls and ceiling mortar.
	Hairline cracks in horizontal RC structural members.
Yellow (D2)	Large patches of mortar falling off walls and ceilings.
	Cracks in structural RC members (beams, columns, shear walls) but to an extent that does not constitute danger of collapse. Slight distortion of structural elements.
Red (D3)	Heavy damage and distortion of structural elements. Large number of crushed structural elements and connections.
	Considerable dislocation of a storey and of the whole building
Black (D4)	Partial or complete collapse (loss of 50% of the building's volume has taken place at one or more floors).

be supposed (due to the strong shaking) that all buildings had at least slight non-structural damage, it was decided not to use the "green" buildings from the Kalamata and Aegion data sets in the vulnerability analysis.

Finally with the exception of the 1986 Kalamata data set, buildings that collapsed partially, extensively or totally were all included in the same red-tag usability class, which also contained buildings that were deemed unsafe for occupation but did not collapse. This problem was overcome because we were able to identify that only one RC building had collapsed in each of the study zones of the Aegion and Lefkas damage surveys, while five collapsed in Kalamata (see the respective sections about each event later on in this paper for more details). For this reason we introduced one more damage level ("black") to capture the proportion of buildings that suffered extensive or complete collapse, which is important information in human casualty estimation scenarios. In this study we use the definition of collapse proposed by the WHE-EERI PAGER (Prompt Assessment of Global Earthquake for Response) program (Pomonis *et al.*, 2009), whereby a building is considered to have collapsed when a 50% volume reduction or more has taken place at one or more floors.

In conclusion for the RC buildings we proposed a 4-level damage scale that we call EPPO+ as shown in Table 2. This damage scale is essentially the same as the one proposed in EPPO (1997) with the addition of the extra damage grade for the collapsed buildings.

2.2. Damage scale for URM buildings

In the case of URM buildings, it was necessary to modify the University of Patras damage scale (used in the 1993 Pyrgos and 1995 Aegion earthquakes) and relate it to the EMS-98 damage scale (Grünthal, 1998). The University of Patras 4-grade damage scale for masonry buildings is defined in Karantoni and Bouckovalas (1997). In addition to each damage grade, a damage degree from 1 to 4 respectively was assigned for each storey of each building (undamaged storeys and buildings were assigned damage degree zero). In the present study the mean damage degree of each building was derived as the mean of the damage degrees assigned to each of the two storeys. We excluded data on 3-storeyed masonry buildings as the small sample does not allow

Table 3 - Correlation between EMS-98 and University of Patras damage scales for URM buildings.

Lefkas (2003)	**Pyrgos (1993), Aegion (1995)**	**Damage characterization**
Damage Grades (EMS-98)	Mean Damage Degree (Univ. Patras)	
D0	0	No damage
D1	0.5	Slight damage
D2	1.0 or 1.5	Moderate damage
D3	2.0 or 2.5	Heavy damage
D4	3.0 or 3.5	Very heavy damage
D5	4.0	Partial or total collapse

reasonable conclusions. In the case of Lefkas Island 2003 earthquake, Karababa and Pomonis (2011) classified the damage levels according to the EMS-98 damage scale after careful examination of the post-earthquake damage inspection forms in the archives of the local Earthquake Rehabilitation Office. The damage data to URM buildings in the city of Kalamata during the 1986 earthquake, although valuable were not used for reasons explained in the next section.

After careful examination the correlation between the two damage scales (University of Patras and EMS-98) shown in Table 3 was proposed and each of the masonry buildings in the University of Patras damage surveys was thus associated with a respective EMS-98 damage grade.

3. Compilation and analysis of the observed damage data sets

3.1. Damage data of the September 13 and 15, 1986 Kalamata earthquakes

On September 13, 1986 at 20:24 local time an earthquake of M_s 6.2 (M_w=6.0) and focal depth of 8 km occurred 12 km north of Kalamata in south-western Peloponnese (Papazachos *et al.*, 1988). Damage was extensive in most parts of the town, as well as some nearby villages and 20 people lost their lives while 330 were injured (82 of which required hospitalization). Many aftershocks followed, the greatest of which occurred two days later and was centred within the town limits and had M_s 5.4 and focal depth 8 km. This aftershock caused an additional 37 injuries and further damage to the already weakened buildings. Kalamata, capital town of the Messinia prefecture, was at the time inhabited by around 43,000 people and spread over an area of around 10 km^2.

The damage distribution was not uniform across the town, with severe damage concentrated in the central and north-eastern parts of the city (Theodoulidis *et al.*, 2008), coinciding with the historic town centre where old masonry buildings prevailed. Damage near the harbour and the coast was limited. This spatial variation in damage severity was attributed to soil conditions as well as source and directivity effects due to the causative fault's proximity (Gariel *et al.*, 1991). A strong motion accelerograph located in the city centre recorded the main shock and aftershock. During the mainshock the horizontal *PGA* was 0.27 g and the peak horizontal velocity 32.3 cm/s,

Table 4 - Damage distribution of RC buildings after the September 13 and 15, 1986 earthquakes near Kalamata.

Structural type (age)	**No. of storeys**	**Type of ground storey**	**Structural class code**	**No. of buildings**	**Percent of buildings by damage grade**			
					Damage Grades (EPPO+)			
					D0-1	D2	D3	D4
RC frame (pre-1987)	1-3	soft-storey	RC2-LP	566	38.7%	59.4%	1.8%	0.2%
		regular	RC2-L	2,937	55.1%	44.1%	0.9%	0.0%
	4-7	soft-storey	RC2-MP	392	15.1%	83.7%	0.3%	1.0%
		regular	RC2-M	309	20.1%	79.0%	1.0%	0.0%
			Total	4,204	46.6%	52.4%	0.9%	0.1%

while the strong motion duration (acceleration over 0.1 g) was just 2.5 s (Anagnostopoulos *et al.*, 1987).

Damage inspection based on the 1984 EPPO guidelines followed immediately after the main shock (Andrikopoulou, 1987; Argyrakis *et al.*, 1987). The whole building stock of the town consisting of 10,171 buildings was inspected giving us a clear picture of the damage levels as a result of the combined effect of the main shock and the aftershock that followed about 36 hours later. We must also point out that the Kalamata damage data are not available on building by building basis, but only as overall damage distributions in the town by: structural type (masonry, mixed, RC); number of floors (1, 2, 3, 4, 5, 6 or 7 floors) and the existence or not of pilotis (soft-storey) or shops at ground floor level.

In 1986 in Kalamata, 41% of the buildings were RC frames with unreinforced clay brick infill walls constructed mostly in the period 1959-1985. These were buildings of 1 to 7 floors, 22.8% of which had soft-storey at ground floor level (open ground floor for car parking or other use, as well as buildings with shops or other commercial use in the ground floor). There were 44 buildings classed as "purple" (damaged beyond repair or collapsed partially or totally) and 893 classed as "red".

Anagnostopoulos *et al.* (1987) give us information and description of the RC buildings that collapsed during the main shock and the aftershocks that followed (4 buildings collapsed during the main shock and 3 during the aftershocks). Based on our proposed definition of collapse (see Table 2) five of these buildings were assigned to damage grade D4 ("black"). Table 4 shows the damage distribution by height (low and mid-rise) and by the existence or not of a soft-storey of the RC buildings in Kalamata. We note that it is not possible to differentiate undamaged from lightly damaged buildings. We also note that the majority of the mid-rise buildings had a soft storey and that 1% collapsed (as did 0.2% of their low-rise counterparts). In addition, we note that among the RC buildings with regular ground floor there was no case of collapse.

In 1986 in Kalamata, 44% of the buildings were old load-bearing URM (mostly rubble or hewn stone or mixed rubble and hewn stone masonry, but also some adobe buildings). In terms of height 98.8% of these were of one or two storeys. In addition 15% of the buildings were of mixed structural type or with mixed masonry materials. In this category are included URM buildings of mixed materials (e.g., rubble and hewn stone, stone and adobe, etc.) as well as buildings that contain both RC and URM sections (e.g., extensions of old masonry buildings with RC, either horizontally or vertically or both).

In total 1,931 URM and 289 mixed structure or mixed masonry material buildings were classed as “purple” (43.2% and 19.3% respectively). One mixed structure building collapsed during the mainshock (Anagnostopoulos *et al.*, 1987). The number of URM and mixed masonry material buildings that collapsed is unfortunately not known. Because the URM and mixed buildings data are incomplete (e.g., we do not know the proportion of various types of masonry, unknown number of buildings that collapsed, unknown types of mixed masonry materials) it was decided not to use these data in the vulnerability analysis. However, we did use the URM data for the estimation of the seismic intensity in Kalamata.

3.2. Damage data of the March 26, 1993 Pyrgos earthquake

On March 26, 1993 at 13:58 local time a moderate magnitude earthquake (M_s=5.5; M_w=5.4) with focal depth of 10-15 km, occurred at a distance of about 3 km north of the town of Pyrgos in north-western Peloponnese (Stavrakakis, 1996). As a result of the earthquake one old woman lost her life whilst trying to escape a building, 16 people were injured and two wings of the Pyrgos hospital were seriously damaged and had to be evacuated. The population of Pyrgos town (capital of the Elia prefecture) was at the time around 22,000 spread over an area of approximately 4 km^2.

In Pyrgos, 66% of the existing buildings were single-storey and 46.5% were old load-bearing masonry structures. More than half of the buildings in Pyrgos (52.2%) were of RC frames with unreinforced clay brick infill panels. Many of the load-bearing masonry buildings are quite old (20.6% of the existing building stock was built before 1946). In addition, at the time of the earthquake the town of Pyrgos was undergoing a construction boom and there were around 1,800 RC buildings constructed following the revision of the Greek earthquake code in 1984.

Although horizontal *PGA* of 0.45 g was recorded in the town centre, damage was not as serious as in the 1986 Kalamata earthquake. Damage to RC buildings was generally slight to moderate with most of the buildings exhibiting non-structural damage to the hollow clay brick infill masonry walls. However, 22 RC buildings of 2-7 storeys had some structural damage, 9 of which were damaged more seriously but were repairable (a very small proportion of the RC buildings in the town). Further details for the RC building damage distributions are not available as the University of Patras damage survey focused on the effects to masonry structures where damage was more serious (Karantoni and Bouckovalas, 1997). The distribution of damage to masonry buildings was not uniform due to local soil conditions and the direction of the fault rupture (Bouckovalas *et al.*, 1996; Stavrakakis, 1996).

In total 1,023 load-bearing masonry buildings in the town centre (approximately a quarter of those existing in Pyrgos) were included in the University of Patras damage survey. All the masonry buildings in the defined study zone were assessed. Analysis showed that 43% were not damaged, while 22% suffered heavy damage. The type of load-bearing masonry proved to be the main factor influencing the relative performance of the masonry buildings, as it was found that the load-bearing adobe masonry (LBAM) suffered more than stone masonry (LBSM) and brick masonry (LBBM)**.** In addition, there were 72 buildings with mixed load-bearing masonry materials such as any combinations of adobe, stone, brick and concrete blocks. Table 5 shows the

Table 5 - Damage distribution of URM buildings by type of masonry and number of floors in the March 26, 1993 earthquakes near Pyrgos.

Masonry material	No. of storeys	Structural class code	No. of buildings	Percent of buildings by damage grade				
				Damage Grades (EMS-98)				
				D1	D2	D3	D4	D5
Adobe	1-2	LBAM-L	150	00.7%	10.7%	9.3%	23.3%	40.0%
Simple stone	1-2	LBSM-L	672	3.9%	22.0%	13.5%	8.6%	3.0%
Clay bricks	1-2	LBBM-L	110	0.0%	9.1%	10.9%	9.1%	6.4%
Mixed masonry materials	1-2	MIXM-L	72	5.6%	16.7%	20.8%	30.6%	6.9%
Total			1,004	3.1%	18.5%	13.1%	12.5%	9.2%

damage distribution by type of masonry building (19 three-storeyed masonry buildings are not included in the table as the sample was deemed too small for definite conclusions).

3.3. Damage data of the June 15, 1995 Aegion earthquake

On June 15, 1995 at 03:15 a.m. local time a strong M_w=6.4 earthquake with focal depth of 14 km struck the town of Aegion in northern Peloponnese and the surrounding villages (Lekidis *et al.,* 1999). The earthquake was centred approximately 18 km NE of the town in the Gulf of Corinth. A strong aftershock (M_w=5.6) followed 15 minutes later causing further damage including the partial or total collapse of a few buildings. As a result sections of two RC buildings (a 4-storey coastal hotel and a 5-storey apartment block in the town centre) collapsed causing the loss of 26 lives. In addition, 4 other RC buildings collapsed outside the town limits of Aegion but did not cause loss of life (these were an industrial building and three low-rise houses with soft-storey at ground level). The population of Aegion in 1995 was approximately 23,000 people.

In 1995 in Aegion town, 53% of the existing buildings were single-storey and just 6.3% had three to seven floors, while 41.6% of the buildings were load-bearing masonry structures with the proportion of adobe buildings being quite significant (26.2%). More than half of the buildings in Aegion (57.7%) was from RC frames with unreinforced clay brick infill panels. Many of the load-bearing masonry buildings were quite old (26.6% of the existing building stock was built before 1946). In addition, there were around 800 RC buildings that were constructed following the 1984 Greek earthquake code revision making this one the first events to test the performance of these buildings under significantly strong ground motion, as the event in Pyrgos town two years earlier was less severe (see also section 3.5 for the characteristics of the strong ground motion recorded in each of the events).

The one strong motion instrument in operation at the time of the main shock in the centre of Aegion (in the Telecom building) recorded horizontal *PGA* of 0.54 g (the highest ever recorded in Greece) and was situated in the immediate vicinity of the collapsed apartment building (Bouckovalas *et al.*, 1999; Lekidis *et al.*, 1999). This recording was also characterized by long-period pulses which resulted in high horizontal velocity (51.8 cm/s). There is evidence in the literature that such long-period pulses are related to directivity phenomena (Bouckovalas *et al.*, 1999). The northern side of Aegion city is essentially bounded by a normal fault running in E-W

Table 6 - Damage distribution for each building class of RC buildings in Aegion after the June 15, 1995 earthquake.

Construction period	No. of storeys	Type of ground storey	Structural class code	No. of buildings	Percent of buildings by damage grade			
					Damage Grades (EPPO+)			
					D0-1	D2	D3	D4
Prior to 1959	1-3	soft-storey	RC1-LP	13	76.9%	15.4%	7.7%	0.0%
		regular	RC1-L	89	61.8%	30.3%	7.9%	0.0%
	4-7	soft-storey	RC1-MP	0	-	-	-	-
		regular	RC1-M	4	25.0%	50.0%	25.0%	0.0%
1959-1984	1-3	soft-storey	RC2-LP	164	82.9%	15.2%	1.8%	0.0%
		regular	RC2-L	537	78.6%	19.9%	1.5%	0.0%
	4-7	soft-storey	RC2-MP	47	55.3%	42.6%	2.1%	0.0%
		regular	RC2-M	95	57.9%	34.7%	6.3%	1.1%
1985-1995	1-3	soft-storey	RC3-LP	42	97.6%	2.4%	0.0%	0.0%
		regular	RC3-L	70	95.7%	4.3%	0.0%	0.0%
	4-7	soft-storey	RC3-MP	50	84.0%	16.0%	0.0%	0.0%
		regular	RC3-M	36	94.4%	5.6%	0.0%	0.0%
	8+	soft-storey	RC3-HP	1	100.0%	0.0%	0.0%	0.0%
		regular	RC3-H	1	0.0%	100.0%	0.0%	0.0%
Total				1,149	77.5%	20.1%	2.3%	0.1%

direction, parallel to the coast. This fault produces a cliff with an almost vertical drop of about 90 m. The residential part of Aegion lies almost entirely on the up-throw region of the fault, while the harbour is built on the down-throw region. Like in the harbour area of Kalamata, damage in the harbour area of Aegion was limited as a result of dampened ground motions in the soft and deep clayey deposits. The absence of damage in the waterfront area of the town becomes more impressive when it is noted that in this area the buildings are very old (some already ruined) and without any seismic resistance provisions (Athanasopoulos *et al.*, 1998).

The University of Patras damage survey (Fardis *et al.*, 1997; Karantoni and Fardis, 2004; Karantoni and Fardis, 2005) was carried-out in the Aegion town centre (included the harbour area) and assessed the damage to all the buildings within the chosen study zone (it contains 2,108 buildings i.e., around 26% of the town's existing building stock at the time of the earthquake). There were 1,149 RC and 859 masonry and mixed structure buildings in the study zone. Most of the damage occurred in the area of the historic town centre in a zone of about 0.2 km^2 (Fardis *et al.*, 1997; Lekkas, 2002). Within the study zone one single RC building collapsed causing the loss of 16 lives (Lekkas *et al.*, 1997; Papazachos and Papazachou, 2003; Karantoni and Fardis, 2004). Analysis of the damage to RC buildings shows that the ratios of "yellow", "red" and "black" were 20.1%, 2.3% and 0.1% respectively. In particular, 28 of the 1,149 inspected RC buildings suffered heavy and in some cases irreparable damage and had to be evacuated. In Table 6 the damage distribution of the RC buildings is presented, where the type of ground floor, the number of floors and the period of construction are the key variables. We note that it is not possible to differentiate

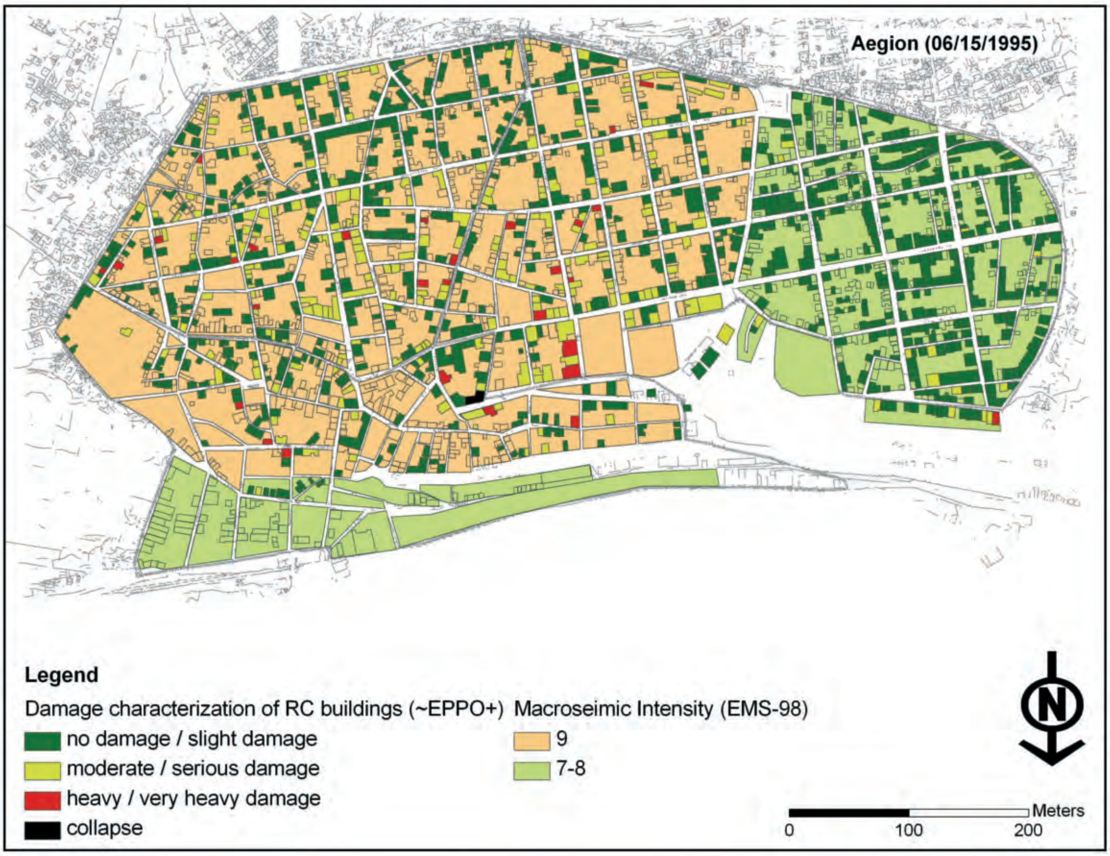

Fig. 1 - Damage distribution of RC buildings in the 1995 Aegion earthquake, according to the EPPO+ damage scale proposed in this study (original data source: Fardis *et al*., 1997). In the present study the damage survey area has been separated into two zones of greatly different damage severity, seen in beige and green colour respectively.

undamaged from lightly damaged buildings. In total, the RC buildings are split into 14 classes (combinations of age, height and ground floor type), however when the sample of buildings in a class is smaller than 20 this class was not considered in the vulnerability analysis. The spatial distribution of the damage is shown in Fig. 1 where it is noted that most of the “yellow” and “red” buildings are in the central and eastern part of the study zone (area with beige background colour). It is also noted that there were very few “yellow” (and just one “red”) buildings in the western part of the study zone.

Comparing the damage distributions of RC buildings in Kalamata and Aegion, we note that in Kalamata there were a lot more buildings in the “yellow” damage grade (52.4% vs. 22.8%) possibly due to the added effect of the strong aftershock. Unlike in Kalamata, in Aegion the existence of soft-storey did not play significant role in the performance of the pre-1985 buildings. In Aegion the buildings built after 1984 revision suffered less damage with none suffering damage degree ≥D3.

The damage inspection of load-bearing masonry buildings in the Aegion study zone was based

Table 7 - Damage distribution of masonry buildings by type of masonry and number of floors in Aegion, after the June 15, 1995 earthquake.

Masonry material	**No. of storeys**	**Structural class code**	**No. of buildings**	**Percent of buildings by damage grade**				
				Damage Grades (EMS-98)				
				D1	D2	D3	D4	D5
Simple stone	1-2	LBSM-L	253	5.1%	24.5%	11.1%	9.5%	8.3%
Adobe	1-2	LBAM-L	426	2.3%	14.6%	16.0%	17.1%	13.8%
Mixed masonry materials	1-2	MIXM-L	52	3.8%	25.0%	13.5%	13.5%	5.8%
Mixed (stone masonry & RC fr.)	1-2	MIXS-L	47	2.1%	4.3%	2.1%	31.9%	0.0%
Brick masonry	1-2	LBBM-L	69	2.9%	7.2%	14.5%	4.3%	2.9%
Concrete block masonry	1-2	LBCB-L	8	0.0%	0.0%	12.5%	0.0%	0.0%
Total			855	3.3%	17.0%	13.5%	12.8%	11.8%

on the assessment of the damage to the external walls of the buildings. The damage degrees were assigned according to the 5-level damage scale of the University of Patras (also used in the 1993 Pyrgos survey) which differs only slightly from the EMS-98 damage scale (see Table 3). The analysis of the data showed that 38.1% suffered serious and heavy damage (≥D3). By comparison in Kalamata 64.3% suffered serious and heavy damage (≥D3). In Table 7 the damage distribution of the load-bearing masonry buildings in the Aegion study zone is presented where the type of masonry material and number of floors are the key variables.

3.4. Damage data of the August 14, 2003 Lefkas Island earthquake

On August 14, 2003 at 08:15 a.m. local time an earthquake of magnitude M_w=6.3 (M_s=6.4) with focal depth of 9 km, occurred near Lefkas Island in the Ionian Sea (Papadimitriou *et al.*, 2006). Lefkas is third in size among the Ionian Islands with a land area of 302.5 km^2. According to the 2001 population census, there are 22,506 permanent residents on the island. The capital of the island is the town of Lefkas on the northern tip of the island. The earthquake's epicentre was 10 km west of the Lefkas town. As a result of the earthquake at least 50 people were injured, while in Lefkas town one 3-storey RC building on pilotis with a timber frame attic extension, gradually constructed in the 1959-1984 period, partially collapsed. Extensive landslides and rock falls took place on the western part of the island seriously injuring some people. The highest damage rates occurred in Lefkas town and villages on the western part of the island, but generally damage was not extensive despite the magnitude and proximity of the earthquake. Lefkas Island belongs to the highest zone of the Greek earthquake code and its buildings (like those of Cephalonia, Zakynthos and Ithaca islands) are most likely to be stronger and less vulnerable.

Lefkas town contains 23% of the island's buildings and its historic centre is founded on soft-loose ground conditions, while the neighbourhoods of Bei and Neapoli are founded on better ground and contain the newer buildings (ITSAK, 2004). In Lefkas town, 57% of the buildings are RC, 6% stone masonry, 9% mixed RC and masonry structures and 28% are either wooden or buildings of LBSM with timber frame elements (Karababa, 2007).

Table 8 - Damage distribution of low-rise RC buildings (regular ground storey, 1-3 storeys) in the 2003 Lefkas Island earthquake.

	No. of storeys	**Structural class code**	**No. of buildings**	**Percent of buildings by damage grade**			
				Damage Grades (EPPO+)			
Construction Period				D1	D2	D3	D4
Pre-1959	1-3	RC1-L	350	12.6%	7.7%	0.0%	0.0%
1959-1984	1-3	RC2-L	3,079	16.6%	4.6%	0.1%	0.0%
1985-1994	1-3	RC3-L	1,496	22.3%	3.4%	0.0%	0.0%
1995-2003	1-3	RC4-L	1,762	9.1%	0.7%	0.0%	0.0%
Total			6,687	15.7%	3.5%	0.1%	0.0%

Karababa (2007) collected all the damage data related to this earthquake from the local Earthquake Rehabilitation Office (included the first and second degree building damage inspection forms) and created a damage database containing 4,211 inspected buildings (which is around 26% of the island's total building stock). In Greece, building assessments are undertaken once the building owner has filed an application requesting an inspection. Evidently, this is dependent on the owner's judgement and consequently, the assessed buildings are in general likely to be found damaged to some degree. The assumption was made that buildings not inspected were undamaged. Although it is acknowledged that other reasons may have led to their exclusion from the inspection process, given that building owners are responsible for the integrity of their building, under Greek law, this assumption is likely to be largely valid. Based on this assumption, the number of undamaged buildings was calculated by subtracting the number of the damaged buildings within each building type from the total number of buildings for the respective type as this was determined through the census data of 2001 (Karababa, 2007).

RC buildings on Lefkas Island are up to 4-storeyed and in 2003 formed about 43% of the building stock, 5% of which have been built before the 1959 earthquake code and 46% built in the period 1959-1984. There are very few RC buildings with soft-storey (around 0.5% of the RC stock) as this practice is avoided in this seismically active region and very few 4-storeyed structures. From the total of 6,687 RC buildings on the island 3.5% (233 buildings) were in the "yellow" class and just 0.1% in the "red" class (7 buildings).

Fig. 2 shows the distribution of the damage by municipal department and by EMS-98 intensity. Table 8 shows the damage distribution of low-rise RC buildings (1 to 3 storeys) without soft-storey by period of construction. This is the first time in Greece where the full suite of RC structures (when sub-divided by their period of construction, i.e., the earthquake code in use at the time of construction) has been tested and for which detailed and reliable damage data sets are available (though only for low-rise structures without soft-storeys, situated in the highest zone of the Greek earthquake code).

It is seen that the performance of low-rise RC buildings with regular ground floor in Lefkas Island as a whole was related to the period of construction as the newer buildings suffered much less damage. It is also seen that damage was much less than in Kalamata and Aegion as these buildings have been designed with higher demands because Lefkas Island is situated in Greece's

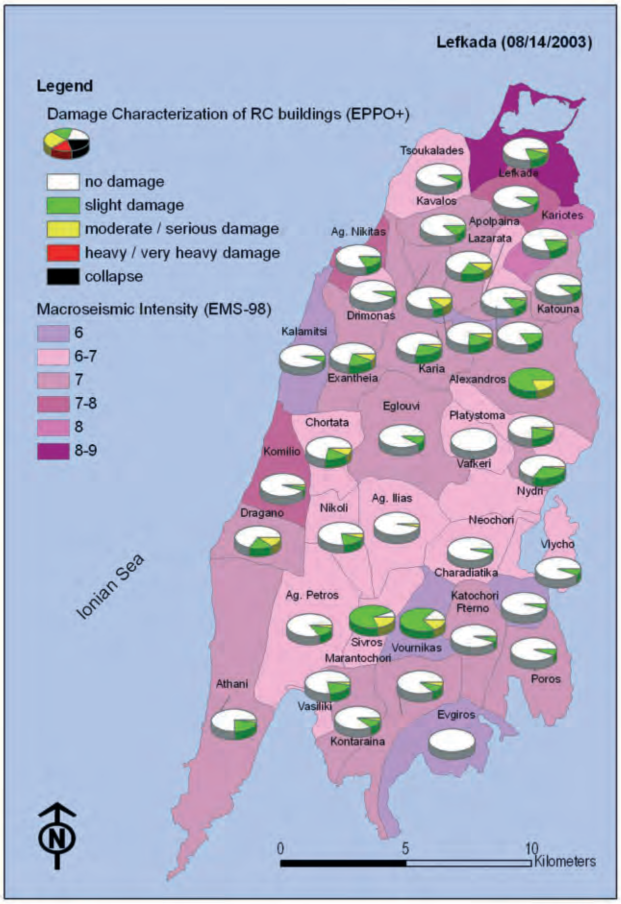

Fig. 2 - RC damage distribution by municipal department and municipality-level EMS-98 intensity in Lefkas Island.

highest earthquake code zone.

On Lefkas Island there are 4 types of vernacular buildings (ITSAK, 2004; Karababa, 2007):

- 1-2 storey LBSM (31% of the total building stock, assigned to LBSM class);
- 1-2 storey load-bearing stone or brick masonry confined in vertical and (or) horizontal RC structural elements which are not designed to perform as moment-resisting frames (14%, assigned to the mixed structure class);
- 1-3 storey timber frame structures (4%) made initially with locally supplied oak, cypress, pine, fir, olive elements and in recent decades from imported timber;
- 1-3 storey mixed LBSM with timber frame (10%).

In Table 9 we show the damage distributions of the first two classes that their vulnerability is examined in this paper.

3.5. Summary of the recorded strong motions during the four events of the damage database

Table 10 summarises the commonly used ground motion parameters of the five strong motion recordings registered within the damage survey zones (peak acceleration, velocity, displacement and bracket duration). These recordings are discussed in detail by Anagnostopoulos *et al.* (1987),

Table 9 - Damage distribution of LBSM and load-bearing masonry mixed with RC frame (with 1-2 storeys and regular ground storey) in the 2003 earthquake in Lefkas Island.

	No. of storeys	**Structural class code**	**No. of buildings**	**Percent of buildings by damage grade**				
				Damage Grades (EMS-98)				
				D1	D2	D3	D4	D5
Simple stone	1-2	LBSM-L	4,819	8.7%	10.0%	10.3%	3.9%	0.0%
Mixed (masonry & RC frame)	1-2	MIXS-L	1,946	6.7%	9.6%	5.3%	0.2%	0.0%
Total			6,765	8.1%	9.9%	8.9%	2.8%	0.0%

Stavrakakis (1996), Lekidis *et al*. (1999) and ITSAK (2004). It is must be noted that these recordings are representative of the ground motion near the recording stations while the damage surveys took place over wider areas with varied ground conditions

In Fig. 3, we see the acceleration response spectra (transversal component) for each of the four main shock recordings. For low and medium-rise RC buildings examined in this study the fundamental periods are expected to be in the range of 0.1-0.6 s. It is seen that ductility demand on these buildings was quite strong in all four events at this period range. The demand is highest in the case of the record in Lefkas town, but also Aegion town. This ductility demand is much higher than the design code coefficients used by Greek engineers which after allowance for safety factor (1.75), increase in allowable stresses for seismic design (20%) and a multi-degree of freedom effect (0.85) result in the case of the pre-1995 buildings (built on average ground conditions) at base shear coefficients equal to 0.12 for Kalamata and Aegion (Lekidis *et al.,* 1999), 0.18 for settlements on Lefkas Island and 0.23 for Lefkas town which lies mostly on unconsolidated ground deposits (ITSAK, 2004).

4. Assessment of EMS-98 intensity in the damage survey areas

The quantification and prediction of damage due to seismic actions to various structural types is an important problem. A growing number of theoretical and experimental investigations as well as field observations after damaging earthquakes, indicate that the *PGA* does not correlate well with the observed structural damage as it does not contain information on the duration or energy content of the ground motion across the frequency range that relates to building structures and influence the damage potential of ground motion (Pomonis *et al.,* 1992; Koliopoulos *et al.*, 1998). Moreover, it is often the case that observed damage data are not the result of one single event or recorded ground motion, but the cumulative effect of a main shock, strong aftershocks and (or) foreshocks that may follow or precede, while in some cases damage from previous earthquakes may also play a role (particularly in regions of high seismicity and on older buildings).

Seismic intensity scales provide an alternative to this problem as they categorize the strength of the ground motion through the careful study of the macroseismic effects of an earthquake in a place. They provide, therefore, a first insight into the strength or damage potential of the experienced ground motion and as a result they continue to have extensive use. Blong (2003)

Table 10 - Peak ground motion parameters and strong motion duration as recorded during the main shocks (and main aftershock in the case of the 1986 Kalamata earthquake) in the four damage survey zones (obtained from ITSAK, 2003).

Location (Date)	**Peak Horizontal Ground Acceleration, *PHGA* (g)**	**Peak Horizontal Ground Velocity, *PHGV* (cm/s)**	**Peak Horizontal Ground Displacement, *PHGD* (cm)**	**Bracket Duration, *BD* (a_g>0.1g) (s)**
Kalamata city centre - Prefecture building - main shock (13.9.1986)	0.27	30.4	5.4	2.3
Kalamata Prefecture Building - main after-shock (15.9.1986)	0.23	22.8	3.3	0.7
Pyrgos city centre (26.3.1993)	0.45	20.8	2.3	1.3
Aegion city centre - Telecom building (15.6.1995)	0.54	51.8	6.2	2.1
Lefkas Town (14.8.2003)	0.42	31.7	4.6	10.7

makes a detailed analysis of the various seismic intensity scales that are in use at present (such as the Modified Mercalli, the MSK, the MCS, the JMA and the EMS-98 scales) and suggests that an intensity scale needs to be dynamic and adaptable to the ever changing conditions, since the ageing of buildings and the development of new earthquake code regulations constantly change the vulnerability of existing building stocks. Such an example is the European Macroseismic Scale (EMS-98, Grünthal, 1998) which was adopted after a 10-year trial and consultation period by the European Seismological Commission and replaces the previously used MSK intensity scale.

The EMS-98 intensity scale more than any of the previous scales gives emphasis to the performance of existing buildings to accurately assess the intensity and incorporates new types of buildings, especially those including earthquake-resistant design features. Building structures of various types (stone masonry, reinforced concrete frames, etc.) are broadly classified into 6 classes (A to F) according to their vulnerability to ground shaking (the level of earthquake design is also taken into account). In addition, clear definitions are given for the various levels of damage (damage grades) for masonry and RC structures respectively [five damage grades – from DG1 for negligible to slight damage to DG5 for destruction (very heavy structural damage)]. In the range of intensities that by definition are capable of causing damage to buildings (V and above) the likely ranges in the proportions of the buildings in each vulnerability class to suffer a certain damage grade are clearly defined. Most importantly, it is probabilistic in its approach to damage; as for any type (strength) of building at a particular level of intensity, damage can be considered as a distribution of damage grades (Musson, 2000). Clear guidelines and explanation are included in the official EMS-98 intensity scale document (Grünthal, 1998), including photos of damage which clearly show the types of damage for each damage grade. These improvements made the EMS-98 scale more robust by reducing the uncertainties associated with intensity

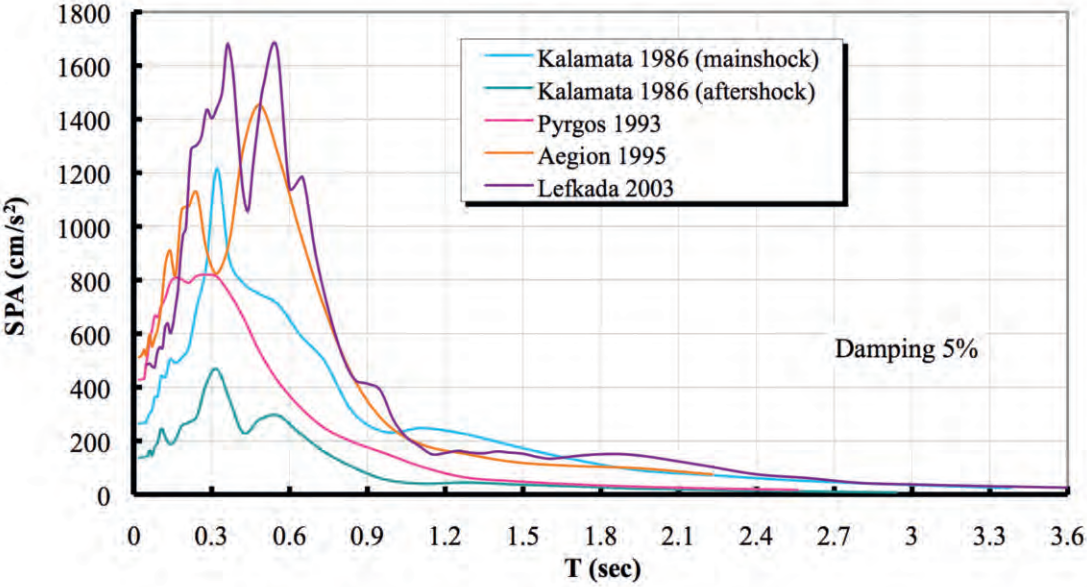

Fig. 3 - Response spectra (transversal component) of examined earthquakes (source: ITSAK, 2003).

assignments using previous macroseismic scales and is thus considered adequate for use in seismic risk assessment (Musson, 2000).

An example of EMS-98 intensity estimation is discussed hereafter related to the Aegion data set (Fig. 1). Following the guidelines of EMS-98 the typologies described in Tables 6 and 7 were assigned to vulnerability classes. RC buildings constructed before 1959 (RC1) were assigned to class C, those constructed with the 1959 code (RC2) to class D and those constructed after 1984 (RC3) to class E. With regard to masonry buildings, adobe and stone masonry (LBAM, LBSM) were assigned to class A. For the case of RC buildings due, to the nature of the Greek post-earthquake building usability assessment data, it was also necessary to correlate the 4-grade EPPO+ damage scale with the 5-grade EMS-98 damage scale (further discussion on this is included in section 5.3 of this paper). Having defined the damage distribution according to the EMS-98 damage scale for each vulnerability class, it was possible to assign an intensity degree for each class and then by taking into account the total number of buildings a weighted mean intensity was estimated. For the case of the 1995 Aegion data set, we estimated intensity VIII-IX for the whole survey zone, IX for the eastern and central part and VII-VIII for the western part (shown in Fig. 1). We note that within the small zone of the Aegion damage survey area (less than 0.5 km^2), depending on structural class quite different intensities were obtained (in this case from intensity VII up to X). Similarly, Tertulliani *et al.* (2011), following the same standard procedure, assigned EMS-98 intensity to downtown L'Aquila (a zone of 2 km^2) affected by the April 6, 2009 earthquake and found that the intensity was VIII or IX.

The EMS-98 intensities estimated for each event's data set are shown in Table 11 (second column from the left) while those assigned by other authors are also shown. General agreement

Table 11 - Estimated macroseismic intensity (I_{EMS}) for each event.

Seismic event	EMS-98 Intensity assigned by this study	Assigned Intensity by Other Authors	References
Kalamata (13/09/1986)	9 (for the city as a whole)	VI to IX	Leventakis *et al.* (1992)
		IX	Papazachos and Papazachou (2003)
		IX	Pomonis *et al.* (2009)
Pyrgos (26/03/1993)	7 (based on damage to masonry buildings)	VI+	Stavrakakis (1996)
		VIII	Lekkas (1996), Lekkas *et al.* (2000)
		VIII	Penelis *et al.* (2002)
Aegion (15/06/1995)	8-9 (for the whole study zone)	VIII	Papazachos and Papazachou (2003)
		VIII	Penelis *et al.* (2002)
		VIII	Pomonis *et al.* (2009)
Lefkas Island (14/08/2003)	6 to 8 (8-9 in Lefkas town)	V to VIII	Papadopoulos *et al.* (2003)
		V to VIII	Papathanassiou and Pavlides (2005)
		VI to VIII	Karababa and Pomonis (2011)

can be observed, despite different methods used in the derivation of intensity by the other authors [in Kalamata (Leventakis *et al.,* 1992) assessed Modified Mercalli intensity distribution throughout the city by combining the results of field and a questionnaire surveys; Lekkas (1996) and Lekkas *et al.* (2000) used geological observations to derive the EMS-92 intensity in Pyrgos during the 1993 earthquake; Stavrakakis (1996) generated a synthetic isoseismal for the Pyrgos 1993 earthquake; Papathanassiou and Pavlides (2005) tested the INQUA scale on the Island of Lefkas; Karababa and Pomonis (2011) used the parameterless scale of intensity (PSI) proposed by Spence *et al.* (1992), on the Island of Lefkas and then derived EMS-98 values based on a correlation between PSI and MSK scales].

It has been shown that peak horizontal ground velocity (*PHGV*) is better correlated to macroseismic intensity than *PGA* in locations where the intensity is greater or equal to VII (Wald *et al.,* 1999), as is the case in all four damage survey zones in this study. Using the proposed *PHGV* to Modified Mercalli intensity conversion equation for Greece by Koliopoulos *et al.* (1998) and the recorded *PHGV* values shown in Table 10, we note that the correlation between the EMS-98 intensities assessed in this study (assumed to be equivalent to the Modified Mercalli intensity) and those derived by the conversion equation is very good for the case of Pyrgos (I_K=7.46), Aegion (I_K=8.54) and Lefkas town (I_K=7.96), but not in the case of Kalamata (I_K=7.91). In Kalamata we estimated EMS-98 intensity IX for the city as a whole as we do not have the damage data at neighbourhood level that would allow us to estimate intensity at a finer resolution. However, the recording station's location (in the Messinia prefecture building) was in a zone that has been assessed by Leventakis *et al.* (1992) as experiencing intensity VIII which correlates very well with the value of intensity predicted by the aforementioned conversion equation.

In terms of the local site effects (topography or soil), EMS-98 indicates that "absolutely no attempt should be made to discard or reduce intensity assignments on the grounds that they were influenced by soil conditions" and advises that "it is also desirable to assign values to locations which are reasonably homogeneous, especially with regard to soil types" and "in the case where a town has areas in which the geotechnical conditions are very different then different intensity values should be assessed for the two parts of the town independently" (Grünthal, 1998). Complying with these guidelines, we proposed different intensity values for the Aegion study zone and across Lefkas Island including Lefkas town whose historic centre is founded on alluvial sediments of loose sand and soft marine clays. Unfortunately, it was not possible to do this in Kalamata, where local site conditions are considered to have played a role in the significant variations in damage severity observed across the town (Anagnostopoulos *et al.,* 1987; Theodoulidis *et al.,* 2008) as the available data are aggregates for the whole town. In Kalamata neighbourhood-level damage data do exist for a subset of 7,101 out of the 10,171 buildings for 26 neighbourhoods but neighbourhood boundaries are approximate and do not correlate well with differing soil conditions across the town (Pomonis *et al.,* 2009).

5. Vulnerability analysis

Observed damage-based seismic fragility curves can be described by (cumulative) normal, lognormal, beta, binomial, or other distributions, provided that sufficient data sets are available for constructing them. The ground motion severity can be described either by intensity scales (which are discrete values) or by instrumental ground motion parameters such as *PGA* or spectral displacement (which are continuous variables) or by the use of the PSI proposed by Spence *et al.* (1992). However because instrumental data in areas where detailed and reliable damage data sets are available are usually not sufficient, analytical methods are often used to derive the fragility curves (Kircher *et al.*, 1997). Hybrid methods combining both observed damage data sets and analytical methods have also been proposed (e.g., Kappos *et al.*, 1998, 2006).

In the present study the severity of the ground motion is described in terms of the EMS-98 macroseismic intensity scale. Assuming that the macroseismic intensity is a continuous variable, cumulative normal distribution curves have been fitted to the damage distribution data sets at each intensity degree for each type of structure. The normal (Gaussian) distribution in its cumulative form has been used in previous seismic vulnerability studies (e.g., Spence *et al.,* 1992; Orsini, 1999; Karababa and Pomonis, 2011). The main hypothesis for the distribution model of the damage grades is that for a generic structure belonging to a specific structural vulnerability class, the intensity at which the structure overcomes a determined threshold of damage is distributed according to a Gaussian model. Though belonging to the same structural vulnerability class, the behaviour of the structures in a class is not identical of course; the results are scattered around the mean and are normally distributed (Orsini, 1999). There is though a fundamental problem with the normal distribution in that it gives positive values of damage probability even for zero values of intensity, however as stated before we consider the present analysis as being valid only for the EMS-98 intensity range of VI to IX.

5.1. Structural types used in the vulnerability analysis

The combination of damage data sets from earthquakes that occurred in different parts of Greece and at different times showed that different methods have been used during the post-earthquake damage assessments and that the damage grades recorded in each case are not identical. This is neither unusual nor unexpected considering that the damage surveys took place across a time span of 17 years. The data set from the 1986 Kalamata earthquake is such a case, where the otherwise valuable information (more than 10,000 buildings subjected to varying degrees of seismic intensity in the range of V to X) are limited in terms of the vulnerability parameters captured (e.g., period of construction, type of load-bearing masonry, typologies of the mixed structures).

An additional problem with the Greek data sets is that in the "green" damage grade it is often not clear if undamaged buildings are included or not. For example in the Kalamata (1986) and Aegion (1995) damage data sets for RC buildings it is stated that the "green" class includes the buildings that were not damaged. Therefore, in the vulnerability analysis for the D1 ("green-tag") damage grade the information from these two data sets was not taken into account. Furthermore, for the derivation of reasonable conclusions we selected structural classes that have been subjected to three or more distinct levels of intensity if the buildings' sample was greater than 20. As a result from the total of 28,747 buildings in the database, only approximately 62.5% took part in the analysis. With this selection process it was possible to assess the vulnerability of ten structural classes. The list of these 10 classes including codification for ease of reference, vertical load-bearing structural system, the period of construction, number of storeys, type of ground floor and the number of buildings of each class used in the analysis are shown in Table 12.

Furthermore, these ten structural classes were sought out in the last building census of Greece (EL. STAT., 2000) in order to estimate the percentage of the Greek building stock that belongs to these classes. According to the available data sets, nine out of ten building classes can be assigned to the building classes in the census (the mixed structures are not clearly specified in the census). It was found that the 9 classes (excluded the mixed structures) cover approximately 66.7% of the building stock in Zone II of the 2004 Greek earthquake code, where approximately 54.5% of the country's building stock is situated. URM buildings (LBSM-L, LBAM-L) are considered in this analysis to have similar vulnerability regardless of earthquake code zone, as construction of load-bearing masonry buildings in Greece has been quite limited from 1960 onwards. In general though, a more thorough analysis would need to consider possible differences in masonry construction across time (Karantoni and Bouckovalas, 1997) and in different parts of the country, but the available data sets did not permit us to consider these factors in this analysis (e.g., lack of information about the period of construction in the data sets of the first 3 earthquakes in this analysis). We thus estimate that including the mixed structures (which could account for approximately 5 to 10% of the existing building stock) the analysed classes cover approximately 50% of the country's existing building stock (which amounted to 4.35 million buildings at the end of 2009).

In Fig. 4 we see the total number of buildings in each earthquake survey by structural type (left) as well as the number of buildings that was used in the vulnerability analysis (right). Unfortunately, only a small part of the Kalamata damage data set could be used because of the aforementioned limitations.

5.2. Derivation of fragility curves for Greek buildings

In the cumulative normal distribution, the probability that under a given macroseismic

Table 12 - Final list of structural classes for which observed damage-based vulnerability analysis was possible and the population of buildings in each structural class.

Structural Class Code	**Type of vertical load-bearing structure**	**Construction period**	**No. of storeys**	**Type of ground floor**	**No. of buildings**
RC1-L	Reinforced Concrete Frames with Infill Masonry Walls	Prior to 1959	1-3	regular	368
RC2-L		1959-1984			4,514
RC2-LP		1959-1984		soft-storey	730
RC2-M		1959- 1984	4-7	regular	404
RC2-MP		1959-1984		soft-storey	439
RC3-L		1985-1995	1-3	regular	1,499
RC4-L		1995-2003			1,762
LBSM-L	Stone Masonry	Mostly prior to 1960	1-2	Regular or shops at ground level	5,727
LBAM-L	Adobe	Prior to 1960			576
MIXS-L	Mixed (masonry & RC frame)	-			1,909

intensity (I) a building suffers damage as described by damage grade D_i or greater, is given by:

$$P\left[D \geq D_i / I\right] = \int_{-\infty}^{I} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(I-\mu)^2}{2\sigma^2}\right] \qquad (1)$$

where: μ is the mean value of intensity I under which 50% of the buildings suffer damage grade D_i and σ is the standard deviation of damage grade D_i.

Therefore, each fragility curve depends on only two parameters, the mean and standard deviation, which are derived by fitting the curve to the cumulative damage distribution data corresponding to each damage grade by minimizing the fit errors. The results of this analysis are shown in Tables 13 to 15 for low-rise load-bearing masonry and mixed structures (1 to 2 floors), low-rise RC (1 to 3 floors), and mid-rise RC (4 to 7 floors) structures, respectively. In addition to mean (μ) and standard deviation (σ) of the normal distribution the coefficients of variation (σ/μ) and correlation (R) are also shown. We note that there is no curve fit for damage grades ≥ D3 ("red") and D4 ("black") for some RC classes as no buildings reached these damage levels in any of the surveyed areas. The standard deviation has been kept constant across the damage grade curves of each structural typology but was increased from 1.15 to 2.75 (lower σ was assigned to the URM buildings and higher σ to the RC buildings). In this way we obtained flattened curves for the newer RC buildings that better fitted the data scatter. Fig. 5 shows the fitted curves and data scatter for the LBSM-L and RC2-L structural classes.

It must be pointed out that in this methodology a circularity of reasoning is taking place, as the EMS-98 intensity for each location has been derived from the observed damage distributions and the fitted fragility curves have intensity as the common denominator. However, we believe this approach is still valid as we derive relative curves for 10 different types of structures, including some typologies that are quite important in Greece but not described specifically in EMS-98 (e.g., RC frames with infill walls built in 4 different time periods according to height

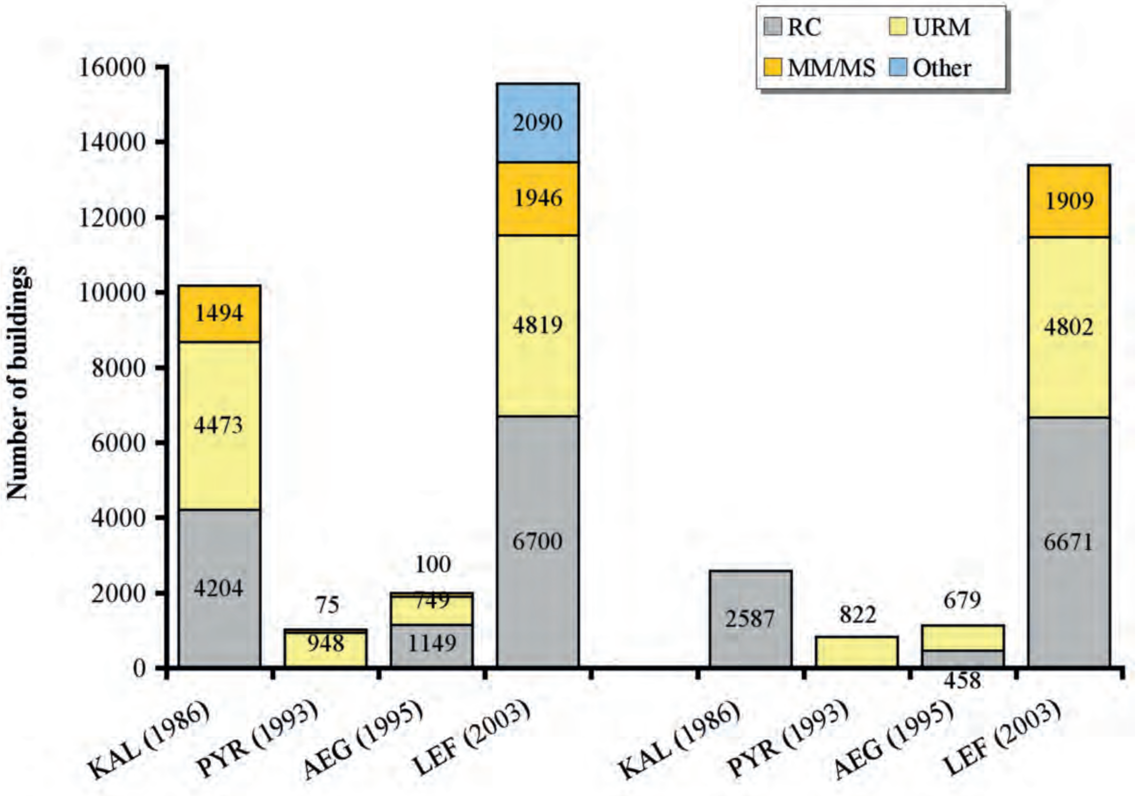

Fig. 4 - Left: number of buildings by type of load-bearing system and event (RC: reinforced concrete, URM: unreinforced masonry, MM/MS: mixed masonry/mixed structure). Right: number of buildings from each event used in the vulnerability analysis.

(low and medium-rise) and according to the existence or not of soft-storey at ground level) whilst also quantifying the uncertainties.

In addition, for RC buildings built after 1959 (RC2, RC3, and RC4) and in order to use the Lefkas Island data set, it was necessary to assume that under the same seismotectonic-geological-local site conditions the RC buildings of Lefkas Island are expected to suffer less damage due to their higher resistance in consequence of the fact that in the island a higher base shear coefficient (ε) is used. According to the 1959 Greek earthquake code (and its 1984 revision), the Island of Lefkas was in zone III where depending on the ground conditions the base shear coefficient was $\varepsilon = 0.08 \div 0.16$, whereas the buildings in Kalamata, Aegion (and Pyrgos) were in zone II with base shear coefficient $\varepsilon = 0.06 \div 0.12$. A similar difference takes place in the 1995 Greek earthquake code (which has four zones, with Lefkas Island being in zone IV) and its 2004 modification (which reverts to three zones, with Lefkas being in zone III). This difference in base shear coefficient and resistance was assumed to be equivalent to half-degree in the EMS-98 intensity scale (i.e., all other things being equal it is assumed that RC buildings in zone II will suffer the same levels of damage as their counterparts in zone III at an intensity that is lower by half-degree).

Table 13 - Parameters of cumulative normal distribution for low-rise (1 to 2 floors) with regular ground floor LBSM and mixed masonry with RC building classes in Greece.

Structural Class Code	**Parameter**	**Damage Grades (EMS-98)**				
		≥D1	≥D2	≥D3	≥D4	D5
LBAM-L	σ_{EMS}	1.15	1.15	1.15	1.15	1.15
	μ_{EMS}	7.53	7.59	8.25	8.95	9.86
	σ/μ	0.153	0.152	0.139	0.128	117
	R	0.265	0.239	0.217	0.032	-0.200
	No. of data sets	4	4	4	4	4
LBSM-L	σ_{EMS}	1.25	1.25	1.25	1.25	1.25
	μ_{EMS}	7.53	7.89	8.95	9.67	10.62
	σ/μ	0.166	0.158	0.140	0.129	0.118
	R	0.794	0.850	0.760	0.894	0.658
	No. of data sets	10	10	10	10	10
MIXS-L	σ_{EMS}	1.75	1.75	1.75	1.75	-
	μ_{EMS}	8.66	9.37	10.91	12.80	-
	σ/μ	0.202	0.187	0.160	0.137	-
	R	0.179	0.032	-0.130	0.978	-
	No. of data sets	5	5	5	5	5

Papaioannou and Papazachos (2000) assessed the earthquake hazard of 144 broad sites across Greece (cities, towns and villages) in terms of the expected macroseismic intensity and *PGA* with a mean return period of 475 years. They reported that in zone IV (of the 1995 code) the average values for these two parameters are 8.2 and 0.37 g respectively, while in zone III they are 7.6 and 0.25 g respectively. The base shear coefficient adopted for soil type B (stiff) in the 1995 Greek earthquake code was 0.36 and 0.24 in zones IV and III respectively, i.e., almost identical to the values derived by Papaioannou and Papazachos (2000). The difference in the average macroseismic intensity with 475 years return period between the two zones is 0.6, i.e., almost the same to our proposed hypothesis.

5.3. Discussion and comparisons with other vulnerability studies

The analysis described in the previous section led to the development of fragility curves for 10 types of structural classes commonly found in Greece. These curves are considered valid for buildings in zone II of the earthquake code in practice during the period 1959-1994, zone III of the earthquake code valid in the period 1995-2003 and for the EMS-98 intensity range VI to IX. The coefficient of correlation (*R*) seen in Tables 13 to 15, is that derived from linear regression between the observed and predicted values respectively and in some cases it is negative. The best fit was obtained for classes LBSM-L, RC2-L, RC2-LP, RC2-M and RC2-MP for most damage grades. The goodness of fit for the remaining 5 types of structural classes (LBAM-L, MIXS-L, RC1-L, RC3-L and RC4-L) is poor due to the scatter of the data and the limited number of data

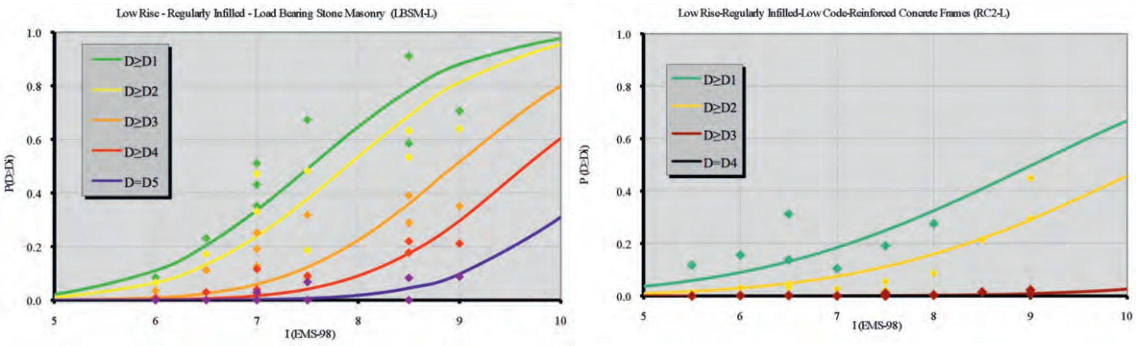

Fig. 5 - Observed damage-based fragility curves for two building classes: 1-2 storey unreinforced stone masonry (left) and 1-3 storey RC frame with infill masonry walls without soft-storey, built in zone II of the Greek earthquake code valid in the 1959-1984 period (right).

sets. The data scatter is also related to inconsistencies between the damage survey and data collection methodologies used in the 4 examined earthquakes as described in sections 3.1 to 3.4, uncertainties in the accuracy of the damage assessments and their correlation with the hereby adopted damage grades for RC and masonry buildings (discussed in sections 2.1 and 2.2). For the case of LBAM-L the data from Pyrgos earthquake, suggesting 40% of the buildings had collapsed, need to be re-examined as we believe that actually most were severely damaged, not collapsed. For the classes MIXS-L, RC1-L, RC3-L and RC4-L we have limited data sets almost exclusively from the 2003 earthquake in Lefkas Island. Therefore, the proposed curves for the latter 5 structural classes should be viewed with caution and as preliminary.

We have compared the curves obtained for the 5 structural classes with good fit to fragility curves proposed by Rossetto and Elnashai (2003), Kappos *et al.* (2006) and Rota *et al.* (2008). The main obstacle in the comparison with these studies has to do with the descriptor of ground motion severity as *PGA*, spectral acceleration or spectral displacement is used. Converting *PGA* or spectral parameters to intensity adds to the uncertainty of the comparisons. On the other hand, the study of Lagomarsino and Giovinazzi (2006), although not based on observed damage data, offers itself for the most direct comparison because it is related to the EMS-98 intensity scale and contains sub-classes of masonry (by type of load-bearing wall material and type of diaphragm) and RC, by number of floors (using height bands identical to those in this study) and ductility class. Comparing macroseismic and mechanical models, Lagomarsino and Giovinazzi (2006) redefined the parameters of vulnerability and capacity curves after cross-validation and calibration providing the potential for advancing each other. Taking their proposed vulnerability and ductility indices (V and Q) for each of the examined structural classes, EMS-98 based fragility curves were obtained using the binomial distribution and were compared with their counterparts in this study. It must be noted though, that because both studies are based on the EMS-98 scale, a certain degree of similarity is expected despite the use of different smoothing functions and models. The results of this comparison are presented and discussed herein.

In Fig. 6 we see the comparison for the LBSM-L and RC2-L classes with: low rise (1-2 floors) simple stone with wooden diaphragms (class code: M3.w_L) and low-rise (1 to 3 floors) medium ductility class RC frames in zone II of the Italian earthquake code (class code: RC1 DCM-II_L)

Table 14 - Parameters of cumulative normal distribution for low-rise (1 to 3 floors) RC building classes in Greece according to the period of construction and the existence or not of a soft-storey.

Structural Class Code	**Parameter**	**Damage Grades (EPPO+)**			
		≥D1	≥D2	≥D3	≥D4
RC1-L (pre-1959)	σ_{EMS}	2.00	2.00	2.00	-
	μ_{EMS}	9.31	9.96	11.99	-
	σ/μ	0.215	0.201	0.167	-
	R	-0.470	0.600	0.847	-
	No. of data sets	5	8	8	8
RC2-L (1959-1984)	σ_{EMS}	2.25	2.25	2.25	-
	μ_{EMS}	9.02	10.24	14.37	-
	σ/μ	0.249	0.220	0.157	-
	R	0.448	0.915	0.793	-
	No. of data sets	7	11	11	11
RC2-LP (1959-1984)	σ_{EMS}	2.10	2.10	2.10	2.10
	μ_{EMS}	8.00	9.85	13.17	15.49
	σ/μ	0.263	0.213	0.159	0.136
	R	0.946	0.740	0.914	0.546
	No. of data sets	4	4	4	4
RC3-L (1985-1994)	σ_{EMS}	2.50	2.50	-	-
	μ_{EMS}	9.15	12.43	-	
	σ/μ	0.273	0.201	-	-
	R	0.000	0.424	-	-
	No. of data sets	7	10	10	10
RC4-L (post-1994)	σ_{EMS}	2.75	2.75	-	-
	μ_{EMS}	10.27	14.34	-	-
	σ/μ	0.268	0.192	-	-
	R	0.210	0.045	-	-
	No. of data sets	7	7	7	7

respectively. We consider these two structural classes in Italy quite similar to the examined Greek classes, as in Greece LBSM-L buildings have almost exclusively wooden diaphragms, while RC2-L buildings in Greece can be considered as having medium ductility as they have been designed according to the 1959 earthquake code. However, it is also noted that the Italian classes do not differentiate between RC buildings with or without soft-storey (pilotis). In addition, we compared this study's class RC2-LP with class RC1 DCM-II_L, as well as this study's classes RC2-M and RC2-MP with class RC1 DCM-II_M of the Italian study.

In the case of LBSM-L, we note that the damage scale used in this study is identical to the EMS-98 damage scale also used in the Italian study, thus direct comparisons can be made for all five damage grades (D1 to D5). We note that in the present study somewhat higher vulnerability

Table 15 - Parameters of cumulative normal distribution for mid-rise (4 to 7 floors) RC building classes constructed in the period 1959-1985 in Greece for regular structures and structures with a soft-storey.

Structural Class Code	**Parameter**	**Damage Grades (EPPO+)**			
		≥D1	≥D2	≥D3	≥D4
RC2-M (1959-1984)	σ_{EMS}	2.10	2.10	2.10	
	μ_{EMS}	7.44	8.69	12.54	4.31
	σ/μ	0.282	0.242	0.167	0.147
	R	0.857	0.929	0.456	0.349
	No. of data sets	4	4	4	4
RC2 MP (1959-1984)	σ_{EMS}	2.15	2.15	2.15	2.15
	μ_{EMS}	7.20	8.25	12.50	14.05
	σ/μ	0.299	0.261	0.172	0.153
	R	0.742	0.656	-0.803	0.500
	No. of data sets	3	3	3	3

is estimated for the Greek stone masonry buildings for all damage grades except grade D1 (slight damage) where we estimated lower probabilities for the intensity range VI to IX.

In the case of RC buildings, the EPPO+ damage scale consists of four instead of five damage grades (D1 to D4) and is based on the EPPO instructions (EPPO, 1997), as described in section 2.1. In addition, the EPPO descriptions for the three-colour tag scheme for RC buildings, do not match very well with the descriptions given for the five damage grades of the EMS-98 scale (Grünthal, 1998). However, after careful examination of the two damage scales we consider that EPPO+ damage grades D1 ("green-tag"), D3 ("red-tag") and D4 ("collapsed") can be considered to be nearly equivalent to EMS-98 damage grades D1, D4 and D5 respectively, while EPPO+ damage grade D2 ("yellow-tag") can be considered to cover the range of damage grades D2 and D3 in EMS-98. Furthermore, it is necessary to point-out the following differences: a) in EPPO-D1 ("green-tag") there is the description "hairline cracks in horizontal RC structural members" that does not exist in EMS-98-D1 that assumes no structural damage at this level (in the following section we shall see that the cost of repair of "green-tag" buildings in Greece is not negligible and it usually ranges between 4 and 7% of a building's replacement value); b) in EMS-98-D4 there is the description "collapse of a single upper floor" which we would assign to EPPO+ damage grade D4 ("black"). These issues need to be kept in mind when interpreting the comparisons between the findings of this study versus those in Lagomarsino and Giovinazzi (2006).

In the case of the RC2-L, RC2-LP vs. RC1 DCM-II_L comparison, we note that in the Italian study the mean value of intensity for damage grades D1 and D2 is I=8.47 and 9.87 respectively, i.e., between the values proposed in this study for RC buildings with and without soft-storey respectively. For damage grade D3 ("red-tag") we estimate that 0.85% and 2.25% of the Greek buildings would suffer this level of damage at intensity IX (non-cumulative), as opposed to 0.48% (non-cumulative) in the Italian study (EMS-98 damage grade D4). For the probability of collapse (D4 in EPPO+) there have been no cases of collapse in any of the four examined events

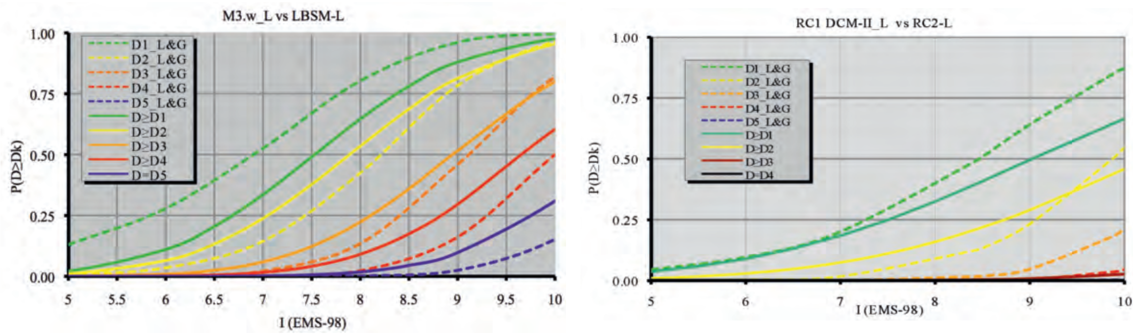

Fig. 6 – Comparison of the LBSM-L (left) and RC2-L (right) fragility curves proposed in this study with those proposed by Lagomarsino and Giovinazzi (2006) for similar structural types.

for the RC2-L class, while we estimate that 0.10% of the buildings with soft-storey would be expected to collapse at intensity IX. The Italian study estimates that 0.02% of the buildings would collapse (EMS-98 damage grade D5) at intensity IX (although some cases of collapse would also be included in damage grade D4 of the EMS-98 scale, which contains buildings where one upper storey collapsed). We conclude that the findings of the two studies are similar for the case of low-rise RC frame buildings.

In the case of the RC2-M, RC2-MP vs. RC1 DCM-II_M comparison, we note that in the Italian study mean value of intensity for damage grades D1 and D2 is I=8.06 and 9.63 respectively, i.e., significantly higher (less vulnerable) than the Greek classes. For damage grade D3 ("red-tag"), we estimate that 4% and 4.25% of the Greek buildings would suffer this level of damage at intensity IX (non-cumulative), as opposed to 1% (non-cumulative) in the Italian study (EMS-98 damage D4). For the probability of collapse (D4 in EPPO+) we estimate that 0.57% and 0.94% of the Greek buildings would be expected to collapse at intensity IX, as opposed to 0.06% in the Italian study (although some more cases of collapse would also be included in damage grade D4 of the EMS-98 scale, which contains buildings where one upper storey collapsed). We conclude that the findings of this study suggest that mid-rise RC frame buildings constructed in the period 1959-1984, situated in zone II of the Greek earthquake code are more vulnerable than suggested by Lagomarsino and Giovinazzi (2006) for their Italian counterparts.

We have also compared our findings with the Modified Mercalli intensity-based DPMs proposed by Eleftheriadou and Karabinis (2008) developed on the basis of observed damage statistics at municipality level from the September 7, 1999 earthquake near Athens. For the masonry buildings we found very good correlation in the intensity range V to VIII even though it was possible to derive only four damage grades from the 1999 Athens building safety assessment data, while the data for intensity IX were not sufficient to draw definite conclusions. Also the Athens 1999 damage data for masonry buildings are unfortunately not differentiated by masonry material (they include adobe, simple stone, brick, mixed masonry, as well as monumental masonry buildings).

We also found quite good correlation with the proposed DPM for RC buildings built in the period 1959-1984 where for damage grades D2 ("yellow-tag") and D3 ("red-tag") we propose lower probabilities in the intensity range VII to IX for classes RC2-L and RC2-LP. This is considered reasonable as the areas affected by the 1999 earthquake near Athens were in that time period in zone I of the Greek earthquake code (the worst affected western suburbs of Athens were subsequently moved to zone II of the 2004 Greek earthquake code). We also note that 33.3% of the inspected buildings included in the DPM, was of mixed structure (RC frames mixed with URM) and that the data did not allow differentiation of the RC buildings by the number of floors and the existence or not of soft-storey. Also the number of undamaged buildings was estimated from the December 2000 Greek buildings census by subtracting the inspected buildings from the municipality-level totals. These shortcomings did not allow more definite comparative conclusions to be drawn against the findings of our study that is based on more detailed damage data.

Furthermore, in terms of RC collapse probability, in the 1999 Athens earthquake, unlike the four events examined in this study, there was an unprecedented number of collapsed buildings. According to Karabinis *et al.* (2003), 69 RC buildings collapsed, in 28 of which there was loss of lives. Of these 54 were low-rise (1-3 floors) and 15 were mid-rise (4-7 floors), while 14 of the 69 had a soft-storey. Only 2 RC buildings built after the 1984 earthquake code revision collapsed. Almost all of the collapsed RC buildings were situated in the zones of intensity VIII and IX shown in Pomonis (2002). The total number of damaged (inspected) RC buildings ("green", "yellow" and "red-tag") in the municipalities assigned intensity VIII and IX by Eleftheriadou and Karabinis (2008) was 12,797 while another circa 30,000 RC buildings were undamaged, i.e., a collapse rate circa 0.20% can be estimated for pre-1985 RC buildings. In our study, probability of collapse from 0 to 0.94% is proposed for the range of intensity VIII and IX for classes RC2-L, RC2-LP, RC2-M and RC2-MP (built in 1959-1984). We consider that the difference in earthquake code zone could be one of the main reasons for the increased number of collapsed RC buildings in Athens, although definite comparisons with our study cannot be drawn due to the incomplete nature of the Athens 1999 damage data.

6. Economic damage factors applicable to Greek URM and RC buildings

For economic loss estimation, we correlated the structural damage grades (D_i) with the respective expected loss of each damage grade. The economic damage index depends on the extent of the damage and can vary for the same building type and damage grade. Usually, for each of the damage grades a central damage factor (CDF_i) and a coefficient of variance are estimated. The CDF is expressed as the ratio of the cost of repair (and in some cases strengthening) to the replacement cost of the building (Kappos *et al.*, 1998; Coburn and Spence, 2002). A better assessment of the economic loss factors is useful not only for loss estimation applications, but also for the better assessment of the cost-benefit potential of various vulnerability mitigation measures.

For load-bearing masonry and mixed structures we used the damage factors proposed by Dolce *et al.* (2006), as actual cost of repair data from Greece are very limited. These are 3.5%; 14.5%; 30.5%; 80.0% and 95.0% for damage grades 1 to 5 respectively (described in Table 3). For each damage grade they also give the parameters of a standard beta probability density function to account for the uncertainty in these factors.

For the damage factors that apply to the damage grades of Greek RC buildings (described in

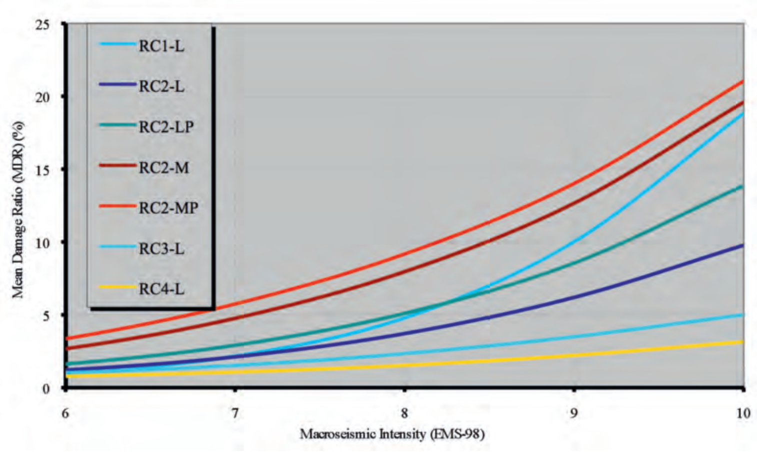

Fig. 7 - Mean Damage Ratio (MDR) as a function of macroseismic intensity (I_{EMS}) for seven classes of RC buildings for which damage data sets were sufficient to develop the vulnerability analysis.

Table 2) we collected data on the cost of repair by damage grade, location, number of storeys and construction period that resulted following the 1999 Athens earthquake, including insurance claims (Karabinis and Baltzopoulou, 2006; Kappos *et al.*, 2007; Vlachos and Vlachos, 2008).

The cost of repair of the “yellow-tagged” RC buildings in particular exhibits a significant degree of scatter as buildings with a variety of damage types (structural and non-structural) are included. Analysis of the cost of repair of 874 government financed “yellow-tag” RC buildings in the municipalities of Aharnes and Ano Liosia (the 2 worst affected by the 1999 Athens earthquake) showed that the *CDF* depends on factors such as (Karabinis and Baltzopoulou, 2006): the intensity of the ground motion, the size of the property, the number of storeys and period of construction, e.g., in Aharnes the *CDF* was equal to 12.7% and in Ano Liosia 19.5%, while buildings built in 1959-84 had *CDF* of 14.4%, those built in 1985-94 had 12.7% and those built in 1995-98 had 11.9% damage factor respectively. We believe that another factor is the existence or not of soft-storey, which was not taken into account in the above studies but contributes to the scatter.

For the “red” RC buildings the damage factor is also varied, despite the fact that in the overwhelming majority of cases a protocol for demolition is issued (100% loss). In case of repairable “red-tag” RC buildings the economic cost factor can range between 40 and 70% of the replacement value and may include strengthening measures. In the case of “green-tag” RC buildings a cost factor of 7.5% was reported.

Kappos *et al.* (2007), using a different data set from the same two municipalities, reported *CDF* of 6.7% for “green”; 17.5% for “yellow” and 68.4% for repaired “red” RC buildings respectively. For the “black” RC buildings the economic loss factor is 100% as these buildings collapsed to such a degree that repair is impossible.

We have also analysed the *CDF’s* derived from insurance claims (Vlachos and Vlachos, 2008). This contains 1,848 claims by damage grade. We found that in the case of “green” and “yellow” buildings the paid insurance claims were broadly on the same level as the government compensation. We found that the *CDF* for “green” buildings was 4.4%, for “yellow” buildings 15.5% and for a few repaired “red” buildings 43.7%. More work is needed with the original data sets of these sources in order to derive the coefficients of variation of the *CDF* per damage grade.

Next the mean damage ratio (*MDR*) was calculated, which is defined as the sum of the products of the probability of occurrence of a certain damage grade (D_i) with the corresponding central damage factor (CDF_i). In Fig. 7 we show the *MDR* curves for seven classes of RC buildings for which damage data sets were sufficient to develop the vulnerability analysis. In this analysis we used the following *CDF*: 5% for "green" (D1) damage grade, 15% for "yellow" (D2) damage grade, 80% for "red" (D3) damage grade and 100% for "black" (D4) damage grade.

7. Conclusions

We have compiled a database containing damage data sets for the most reliable and detailed damage surveys carried-out in Greece following four small to moderate magnitude earthquakes that affected parts of the Peloponnese peninsula and the Island of Lefkas in western Greece during the period 1986 to 2003. We present details of the damage distributions for various structural classes for each of the examined events and explain possible reasons for these distributions including reference to recorded strong ground motions and soil conditions. This compilation of damage data sets allowed development of vulnerability functions (fragility curves) for several commonly found in Greece structural vulnerability classes. The database contains circa 29,000 buildings subjected to ground motion intensity in the range VI to IX. The data sets consist of low-rise URM buildings [mostly cut and (or) rubble stone and adobe blocks] as well as buildings of mixed structure [types of URM mixed with RC frame extensions in the horizontal and (or) vertical direction or masonry confined in vertical and (or) horizontal RC structural elements] or masonry with mixed materials (e.g., adobe and rubble, stone or brick and concrete block, etc.). They also contain RC frame structures with masonry infill panels with or without soft-storey of 1 to 7 floors, built according to three different earthquake codes as well as before the application of earthquake codes in Greece (first introduced in 1959).

Homogenization of the collected data sets was necessary as they originated from not only different areas but they were derived using different post-earthquake damage assessment procedures. Development of homogenized damage scales for masonry and RC structures, through the detailed qualitative descriptions of the original damage scales, applicable to the specifics of Greek post-earthquake damage surveys as these have evolved over the examined period permitted us to define more accurately the damage grade distribution for all available structural classes and events. The proposed damage scales for masonry and RC structures contain 5 and 4 damage grades respectively. Particular emphasis was given to obtain accurately the number of collapsed buildings which are responsible for the greatest part of human casualties in Greek earthquakes. We were thus able to derive better constrained collapse probabilities under increasing intensities which are important in human casualty estimation models as well as in cost-benefit analysis of mitigation measures. Furthermore, the database allowed cross event comparisons, better estimation of macroseismic intensities and observed damage-based vulnerability analysis to be made. As a result we were able to derive fragility curves for the defined damage grades for 10 structural types common in Greece that constitute approximately 50% of the country's existing building stock. Good fit has been obtained only for 5 of the 10 examined structural classes as data are not sufficient for some classes (e.g., new RC buildings

RC3-L and RC4-L or mixed structure buildings MIXS-L) or less reliable (LBAM-L).

The vulnerability analysis showed that stone masonry buildings in Greece being more than 50 years old (as the practice of URM construction has been gradually phased out since the 1960s) are quite vulnerable and in need of strengthening measures. Greek RC frame structures constructed prior to 1985 are also shown to be more vulnerable than their more recent counterparts. In Greece, 65% of the RC building stock was built prior to 1985. The problem of RC buildings with soft-storeys is another concern as these buildings are quite common (approximately 25% of Greek RC buildings have this feature) and have been shown to be more vulnerable than their counterparts with regular ground floors especially when built prior to 1985.

We carried out comparisons with a number of other recent studies on the vulnerability of Greek and European (in particularly Italian) buildings and drew conclusions about the similarities and dissimilarities with our study. Although it is hard to find identical typologies and to define a common ground motion parameter, quite similar trends have been pinpointed between the proposed set of fragility curves and the one of Lagomarsino and Giovinazzi (2006) for LBSM. For RC buildings, the differences between the EMS-98 and the EPPO+ damage scale used in our study can unavoidably lead to broader comparisons, but the exceedance probabilities remain relatively low for “yellow” and “red” tagged buildings and EMS-98 below IX in both studies.

The derived vulnerability curves in combination with *CDFs* gave us the MDRs for the examined structural classes which can be used for loss estimation scenarios. Through these scenarios we can estimate the expected financial losses of an earthquake of a given intensity in an area, as well as how potential losses could be mitigated through various types of strengthening measures. The effectiveness of various loss mitigation measures can then be assessed using standard cost-benefit analysis which is the subject of an accompanying paper, with application to the buildings of Pylos town in south-western Peloponnese.

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REFERENCES

Anagnostopoulos S., Rinaldis D., Lekidis V., Margaris V. and Theodulidis N.; 1987: *The Kalamata, Greece, earthquake of September 13, 1986*. Earthquake Spectra, **3**, 365-386.

Andrikopoulou K.; 1987: *Damage assessment from the earthquakes of Kalamata on 1986-correlation of damage distribution with the soil conditions of Kalamata*. Bull. Int. Inst. Seismol. Earthquake Eng., **23**, 169-188.

Argyrakis K., Kountouris G. and Ioannidis K.; 1987: *Damage assessment after the 1986 Kalamata earthquake*. Report of the working group for the Earthquake Planning and Protection Organization of Greece (in Greek).

Athanasopoulos G.A., Pelekis P.C. and Leonidou E.A.; 1998: *Effects of surface topography and soil conditions on the seismic ground response - including liquefaction - in the Egion (Greece) 15/6/1995 earthquake*. In: Proc. 11th European Conference on Earthquake Engineering, 12 pp.

Blong R.; 2003: *A review of damage intensity scales*. Nat. Hazards, **29**, 57-76.

Bouckovalas G., Anagnostopoulos A., Kapenis A. and Karantoni T.; 1996: *Analysis of soil effects and distribution of* *damage from the Pyrgos 1993 (Greece) earthquake*. Geotech. Geol. Eng., **14**, 111-128.

Bouckovalas G., Gazetas G. and Papadimitriou A.; 1999: *Geotechnical aspects of the 1995 Aegion (Greece) earthquake*. In: Proc. 2nd Int. Conf. Geotech. Earthquake Eng., Lisbon, Portugal, Vol. 2, pp. 739-748.

Coburn A. and Spence R.; 2002: *Earthquake protection, 2nd edition*. John Wiley & Sons Ltd, West Sussex, U.K., 420 pp.

Colombi M., Borzi B., Crowley H., Onida M., Meroni F. and Pinho R.; 2008: *Deriving vulnerability curves using Italian earthquake damage data*. Bull. Earthquake Eng., **6**, 485-504.

Dandoulaki M.; 2008: *Seismic disaster risk as a basis for decision support in earthquake protection: the 1996 Konitsa earthquakes*. In: Proc. 3rd Greece National Conf. Earthquake Eng., Athens, Greece, Paper 2005.

Dandoulaki M., Panoutsopoulou M. and Ioannides K.; 1998: *An overview of post-earthquake building inspection practices in Greece and the introduction of a rapid building usability evaluation procedure after the 1996 Konitsa earthquake*. In: Proc. 11th Eur. Conf. Earthquake Eng., Paris, France, 11 pp.

Dolce M., Kappos A., Masia 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**, 357-371.

Eleftheriadou A.K. and Karabinis A.I.; 2008: *Damage probability matrices derived from earthquake statistical data*. In: Proc. 14th World Conf. Earthquake Eng., Beijing, China, 10 pp.

EL.STAT.; 2000: *National Buildings Census of Greece.* Hellenic Statistical Authority, December 2000.

EPPO; 1984: *Post-earthquake damage inspection of buildings: guidelines and forms for post-earthquake damage surveys*. Earthquake Prot. Plann. Organiz., Athens, Greece (in Greek).

EPPO; 1997: *Instructions and forms for post-earthquake usability assessment of buildings*. Earthquake Prot. Plann. Organiz., Athens, Greece.

Fardis M., Karantoni F. and Kosmopoulos A.; 1997: *Statistical study of damage due to Aegion earthquake of 15-6-95*. Report to the Earthquake Plann. Prot. Organiz. (in Greek).

Gariel J.-C., Bard P.Y. and Pitilakis K.; 1991: *A theoretical investigation of source, path and site effect during the 1986 Kalamata earthquake (Greece)*. Geophys. J. Int., **104**, 165-177.

Gaspari M.; 2009: *Assessment of the earthquake vulnerability of low-rise buildings in Greece with application in Pylos town (Messinia prefecture).* Master of Science Thesis, Department of Geology and Geoenvironment, National Kapodistrian University of Athens, Cross-Institutional Post-Graduate Programme on the Prevention and Management of Natural Catastrophes, May 2009, 144 pp. (in Greek).

Grünthal G. (ed); 1998: *European Macroseismic Scale 1998.* Cahiers du Centre Europeen de Geodynamique et de Seismologie, vol. 15, Centre Europeen de Geodynamique et de Seismologie, Luxembourg, 99 pp.

ITSAK; 2003: *$HEAD_{v1.0}$, Hellenic Accelerogram Database*. Institute of Engineering Seismology & Earthquake Engineering, Geodynamic Institute National Observatory of Athens, Geophysical Laboratory Aristotle University of Thessaloniki and the Earthquake Planning and Protection Organization.

ITSAK; 2004: *The earthquake of Lefkada (M=6.2) 14 August 2003*. Technical Chamber of Greece, Institute of Technical Seismology and Antiseismic Structures, TEE editions (in Greek).

Kappos A. and Panagopoulos G.; 2010: *Fragility curves for reinforced concrete buildings in Greece*. Struct. Infrastruct. Eng., **6**, 39-53.

Kappos A., Stylianidis K. and Pitilakis K.; 1998: *Development of seismic risk scenarios based on a hybrid method of vulnerability assessment*. Nat. Hazards, **17**, 177-192.

Kappos A., Pitilakis K., Morfidis K. and Hatzinikolaou N.; 2002: *Vulnerability and risk study of Volos (Greece) metropolitan area*. In: Proc. 12th Eur. Conf. Earthquake Eng., London, UK, Paper 074.

Kappos A., Panagopoulos G., Panagiotopoulos Ch. and Penelis G.; 2006: *A hybrid method for the vulnerability assessment of R/C and URM buildings*. Bull. Earthquake Eng., **4**, 391-413.

Kappos A., 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*. Earthquake Spectra, **23**, 333-355.

Karababa F.; 2007: *Local seismic construction practices as a means to vulnerability reduction and sustainable development*. PhD Dissertation, Department of Engineering, Cambridge University, Cambridge, UK.

Karababa F. and Pomonis A.; 2011: *Damage data analysis and vulnerability estimation following the August 14, 2003 Lefkada Island, Greece, Earthquake*. Bull. Earthquake Eng., **9**, 1015-1046.

Karabinis A. and Baltzopoulou A.; 2006: *Correlation of damage grade and cost of repair of buildings from the Athens earthquake on September 7, 1999*. In: Proc. 15th Conf. Reinf. Concr., Alexandroupolis, Greece, vol. B3, pp. 305-314 (in Greek).

Karabinis A., Plesias A., Fotopoulou M. and Avramopoulos I.; 2003: *Conclusions on the earthquake vulnerability of buildings from the Athens earthquake of 7 September 1999*. In: Proc. 14th Greek Reinf. Concr. Conf., Kos, Greece, pp. 520-531 (in Greek).

Karantoni F. and Bouckovalas G.; 1997: *Description and analysis of building damage due to Pyrgos, Greece earthquake*. Soil Dyn. Earthquake Eng., **16**, 141-150.

Karantoni F. and Fardis M.; 2004: *Damage to reinforced concrete buildings due to the Aegion, (GR) 1995 earthquake*. In: Proc. Int. Symp. Durability, Maintenance Concr. Struct., Dubrovnik, Croatia, pp. 249-256.

Karantoni F. and Fardis M.; 2005: *Damage to masonry buildings due to the Aegion (GR) 1995 earthquake*. Struct. Stud., Repairs, Maintenance Heritage Archit. IX, **83**, 191-201.

Kircher C.A., Nassar A.A., Kustu O. and Holmes W.T.; 1997: *Development of building damage functions for earthquake loss estimation*. Earthquake Spectra, **13**, 663-682.

Koliopoulos P., Margaris B. and Klimis N.; 1998: *Duration and energy characteristics of Greek strong motion records*. J. Earthquake Eng., **2**, 391-417.

Lagomarsino S. and Giovinazzi S.; 2006: *Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings*. Bull. Earthquake Eng., **4**, 415-443.

Lekidis V., Karakostas C., Dimitriou P., Margaris B., Kalogeras I. and Theodulidis N.; 1999: *The Aigio (Greece) seismic sequence of June 1995: seismological, strong motion data and effects of the earthquakes on structures*. J. Earthquake Eng., **3**, 349-380.

Lekkas E.; 1996: *Pyrgos earthquake damages (based on E.M.S.-1992) in relation with geological and geotechnical conditions*. Soil Dyn. Earthquake Eng., **15**, 61-68.

Lekkas E.; 2002: *The role of earthquake-related effects in urban complexes.* Natural Hazards, **25**, 23–35.

Lekkas E., Lozios S., Kranis H. and Skourtsos E.; 1997: *Linear damage distribution and seismic fractures at the Egion earthquake (15 June 1995, Greece)*. Earthquake Resistant Engineering Structures, Advances in Earthquake Engineering, Computational Mechanics Publications, **2**, 37-46.

Lekkas E., Fountoulis I. and Papanikolaou D.; 2000: *Intensity distribution and neotectonic macrostructure Pyrgos earthquake data (26 March 1993, Greece)*. Nat. Hazards, **21**, 19-33.

Leventakis G., Lekidis V., Papaioannou Ch., Zacharopoulos S., Tsokas G. and Kiratzi A.; 1992: *Isoseismal maps for the Kalamata town due to earthquakes of September 1986*. In: Proc. 1st Greek Nat. Conf. Earthquake Eng. (in Greek).

Musson R.M.W.; 2000: *Intensity-based seismic risk assessment.* Soil Dynamics and Earthquake Engineering, **20**, 353-360.

Orsini G.; 1999: *A model for buildings' vulnerability assessment using the parameterless scale of seismic intensity (PSI).* Earthquake Spectra, **15**, 463-483.

Papadimitriou P., Kaviris G. and Makropoulos K.; 2006: *The M_W=6.3 2003 Lefkada earthquake (Greece) and induced stress transfer changes*. Tectonophys., **423**, 73-82.

Papadopoulos G., Karastathis V., Ganas A., Pavlides S., Fokaefs A. and Orfanogiannaki K.; 2003: *The Lefkada, Ionian sea (Greece), shock (M_w=6.2) of 14 August 2003: evidence for the characteristics earthquake from seismicity and ground failures*. Earth Planet. Space, **55**, 713-718.

Papaioannou Ch.A. and Papazachos B.C.; 2000: *Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources*. Bull. Seismol. Soc. Am., **90**, 22-33.

Papathanassiou G. and Pavlides S.; 2005: *Using the INQUA scale for the assessment of intensity: case study of 14/08/2003 Lefkada earthquakes, Greece*. Final Meeting, Dark Nature-Rapid Natural Change and Human Responses, Como, Italy, pp. 73-74.

Papazachos B. and Papazachou K.; 2003: *Earthquakes in Greece*. Ziti publications, Thessaloniki, 286 pp. (in Greek).

Papazachos B., Kiratzi A., Karakostas B., Panagiotopoulos D., Scordilis E. and Mountrakis D.; 1988: *Surface fault traces, fault plane solution and spatial distribution of the aftershocks of the September 13, 1986 earthquake of*

Kalamata (Southern Greece). Pageoph, **126**, 55-68.

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*. In: Proc. 9th World Conf. Earthquake Eng., Tokyo-Kyoto, Japan, vol. VII, pp. 187-192.

Penelis G.G., Kappos A., Stylianidis K. and Lagomarsino S.; 2002: *Statistical assessment of the vulnerability of unreinforced masonry buildings*. In: Proc. Int. Conf. Earthquake Loss Estimation and Risk Reduction, Bucharest, Romania, 13 pp.

Pomonis A.; 2002: *The Mount Parnitha (Athens) earthquake of September 7, 1999: a disaster management perspective*. Nat. Hazards, **27**, 171-199.

Pomonis A., Coburn A.W. and Spence R.J.S.; 1992: *Strong ground motion and damage to masonry buildings as revealed by damage surveys near recording instruments*. The Martin Centre for Architectural and Urban Studies, Internal Report, Cambridge, UK.

Pomonis A., Kappos A., Karababa F. and Panagopoulos G., 2009: *Seismic vulnerability and collapse probability assessment of buildings in Greece*. In: Proc. 2nd Int. Workshop Disaster Casualties, University of Cambridge, UK, 15 pp.

Rossetto T. and Elnashai A.; 2003: *Derivation of vulnerability functions for European-type RC structures based on observational data*. Eng. Struct., **25**, 1241-1263.

Rota M., Penna A. and Strobbia C.; 2008: *Processing Italian damage data to derive typological fragility curves*. Soil Dyn. Earthquake Eng., **28**, 933-947.

Spence R.J.S., Coburn A.W., Pomonis A. and Sakai S.; 1992: *Correlation of ground motion with building damage: the definition of a new damage based seismic intensity scale*. In: Proc. 10th World Conf. Earthquake Eng., Rotterdam, Netherlands, pp. 551-556.

Stavrakakis G.; 1996: *Strong motion records and synthetic isoseismals of the Pyrgos, Peloponnisos, Southern Greece, earthquake sequence of March 26, 1993*. Pageoph, **146**, 147-161.

Tertulliani A., Arcoraci L., Berardi M., Bernardini F., Camassi R., Castellano C., Del Mese S., Ercolani E., Graziani L., Leschiutta I., Rossi A. and Vecchi M.; 2011: *An application of EMS98 in a medium-sized city: the case of L'Aquila (Central Italy) after the April 6, 2009 Mw 6.3 earthquake*. Bull. Earthquake Eng., **9**, 67-80.

Theodoulidis N., Cultrera G., De Rubeis V., Cara F., Panou A., Pagani M. and Teves-Costa P.; 2008: *Correlation between damage distribution and ambient noise H/V spectral ratio: the SESAME project results*. Bull. Earthquake Eng., **6**, 109-140.

Vlachos I. and Vlachos S.; 2008: *Correlation of financial losses due to earthquake with the structural characteristics of buildings*. In: Proc. 3rd Greek Nat. Conf. Earthquake Eng., Athens, Greece (in Greek).

Wald D.J., Quitoriano V., Heaton T.H. and Kanamori H.; 1999: *Relationships between peak ground acceleration, peak ground velocity and Modified Mercalli Intensity in California*. Earthquake Spectra, **15**, 557-564.

Whitman R., Reed J. and Hong S.; 1973: *Earthquake damage probability matrices*. In: Proc. 5th World Conf. Earthquake Eng., Roma, Italy, vol. 2, pp. 2531-2540.

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