SEISMIC VULNERABILITY AND COLLAPSE PROBABILITY ASSESSMENT OF BUILDINGS IN GREECE

A. Pomonis[1], A. Kappos[2], F. Karababa[3] and G. Panagopoulos[4]

[1] *Risk Management Solutions, Greece*
[2] *Professor, Dept. of Civil Engineering, Aristotle University of Thessaloniki, Greece*
[3] *Earthquake Engineer (PhD), PartnerRe, Zurich*
[4] *PhD Candidate, Dept. of Civil Engineering, Aristotle University of Thessaloniki, Greece*
Email: tony_pom@otenet.gr

ABSTRACT

The present paper focuses on the assessment of seismic vulnerability of buildings in Greece addressing all common typologies, with emphasis on collapse probability, which is directly related to the level of losses (casualties and economic losses). Two different approaches are presented for estimating the collapse probability of different types of buildings for the common values of the Modified Mercalli intensity (VI to IX), one based entirely on the processing of statistical data from past earthquakes in Greece, and one making use of hybrid (analytical and empirical) vulnerability curves; the percentage of population living or working in each building type is also estimated. Finally, some first comparisons with similar results from various other countries are presented.

1. INTRODUCTION

The primary incentive for this paper came from the PAGER (Prompt Assessment of Global Earthquake for Response) project carried out by the American U.S. Geological Survey in cooperation with WHE (World Housing Encyclopedia), a common action of EERI (Earthquake Engineering Research Institute) and IAEE (International Association for Earthquake Engineering). The aim of the project is to establish, with the aid of worldwide experts, an international database of seismic vulnerability for all building typologies commonly found in all countries, focusing on collapse probabilities at each level of macroseismic intensity, which is directly related to the level of losses (casualties and economic losses). The overriding aim of PAGER is to create a system which will support post-seismic decision-making (e.g., decisions regarding the provision and management of humanitarian aid) prior to the collection of information from on-site damage inspections. An additional use of the system will be the development of 'scenarios' vital for the management of seismic risk worldwide. The first two authors of this paper were solicited to contribute their expertise with regards to the Greek territory and thus contribute to the ambitious goals of this project. Two teams were subsequently formed (RMS and AUTh), which although they consulted independently using different methodologies and provided alternative approaches for the Greek building stock, they maintained systematic communication and cooperation with each other.

This paper presents the procedures followed to establish the building typologies found in Greece (to be used in the assessment of seismic vulnerability) and the estimation of collapse probabilities for each building typology and for each of the common values of MMI-EMS macroseismic intensity (VI to IX), as well as some first comparisons with similar results from various other countries.

2. RESEARCH QUESTION-RESEARCH AIMS

The main aim of USGS/WHE with regard to the PAGER project was the development of a rapid post-seismic loss assessment (primarily in terms of human casualties). The relevant questionnaire which was developed and distributed for completion by worldwide experts included the following fields:

1. *Type or material of construction.* This requires selecting the most suitable entry from a table of potential categories based on construction materials and load bearing structural systems. The table forms part of the PAGER framework, but is not exhaustive and allows for the addition of new categories (or sub-categories) to ensure the accurate representation of the building stock of the country in consideration.
2. Description of the structural form.
3. Estimation of the collapse probability (%) for each building typology when subjected to a seismic action of a given intensity (the required intensity ranges between VI to IX).
4. The population percentage that resides in each building typology disaggregated into rural and urban areas.
5. The *working* population percentage that works in each building typology disaggregated into rural and urban areas.
6. The maximum average number of occupants for each building typology.

It should be emphasized that the procedure followed here for the purposes of PAGER differs significantly from a 'typical' seismic vulnerability assessment (e.g., through the use of damage probability matrices). A 'typical' assessment seeks to determine the degree of damage (in structural or economic terms) at each seismic intensity level. In many cases the degree of damage corresponding to partial or total collapse includes buildings which are demolished after an earthquake because their repair-retrofit is considered not feasible or uneconomical. Although in economic terms the outcome of this inclusion would be the same (cost of repair = cost of replacement), in terms of human losses (injuries/deaths) the difference would be very considerable.

For example, in the earthquake of September 7, 1999 near Athens, the number of buildings assessed as "red" i.e., those buildings that were classified as uninhabitable or dangerous in the immediate post-earthquake damage-usability evaluation surveys, was 4682 (4220 residential and 462 non-residential buildings). Many of the 'red-tagged' buildings were subsequently demolished and reconstructed while some were repaired and others remained vacant. However lives were lost in only 27 of these buildings (120 of the 143 deaths that occurred in that earthquake have been associated with the collapse of these buildings), while 45% of the total lives lost was the result of the collapse of just 7 industrial buildings (Pomonis, 2002).

It should be noted that in the previously mentioned 'typical' vulnerability assessments, the number of casualties (in the rare cases where this is attempted to be quantified for the completeness of the relevant seismic risk scenario) is estimated through internationally developed empirical models, e.g., HAZUS (FEMA-NIBS 2003), Coburn and Spence (2002), as a function of the percentage of buildings exhibiting the highest grade of damage (partial or total collapse).

The PAGER methodology therefore aims to rapidly estimate human casualties from earthquakes based on the fact that most earthquake fatalities around the globe are linked to the collapse of buildings (Allen et al., 2009). A study into the causes of death from earthquakes in the period 1900-1999 (1.6 million victims worldwide) estimated that approximately 70-75% of lives were lost due to building collapse, while the remaining 25-30% due to other causes such as, tsunami, landslides and fire following the seismic event (Spence, 2003). This continues to be the case to this day despite the 2004 Indian Ocean tsunami which killed 228,000 people, because an additional 240,000 building-collapse-related deaths took place in the 2000-2008 period, bringing the total life loss in the 1900-2008 period to nearly 2.15 million people (assuming that the loss of life in the 1976 Tangshan earthquake is as officially reported (243,000) instead of unofficial estimates of as many as 655,000 deaths). 92% of the global fatalities of the last 11 decades have taken place in 51 earthquakes that have killed 5,000 or more people and 87% in just 34 events that killed 10,000 or more people. A detailed reappraisal of these events as well as other great earthquakes before is needed to shed more light into the issue of the causes of loss of life during earthquakes around the world, not the least because there are considerable uncertainties as to the extent of human losses and injuries in some of these events with secondary hazards such as landslides, flooding and fire following playing a significant role in some cases. A striking example is the December 25, 1932 Gansu province earthquake in China (M=7.6) which in some catalogues (e.g. in Utsu's catalogue) is reported to have caused the death of 275 people while in others it is said to have killed 70,000. Actually several more 20th century earthquakes in China are the subject of significant uncertainty. Another often misquoted historic event is the September 30, 1139 earthquake in Ganjak (in present day Azerbaijan) which may have caused the death of 230,000 people, but this death toll is usually wrongly attributed to an earthquake(s) that damaged the city of Aleppo in Syria in October 1138 (Ambraseys, 2004) having caused perhaps less than 1,000 fatalities.

Despite progress in many countries in the design of earthquake resistant structures, the current decade has unfortunately become the worst decade since 1900, life losses having reached 471,000, followed by the 450,000 deaths in the 1920's and the 428,000 in the 1970's. Figure 1 shows that extreme variations exist in the temporal distribution of global earthquake deaths which is due to the spatial variation of earthquake activity related to the populated areas of the world but could also relate to variations in global earthquake energy release during the respective periods. We see differences in the number of fatalities on a decadal basis that reach as much as 30 times (e.g. 471,000 killed in the current decade versus the circa 16,000 killed in the 1950's). The data are shown in terms of overlapping decades (e.g. 1900-1909, 1905-1914 and so on). In addition we see that since about 1975 the number of catalogued fatal events has increased significantly due to better reporting and the continuing expansion of populated areas around the globe (the number of catalogued events in each decadal period is seen in the right-hand column of the chart; the total number of catalogued events is 1580 until the end of 2008). When decadal global earthquake fatalities are normalized for global population we notice an even greater spread with the decadal global earthquake fatality rate (per 100,000 population) ranging from 23.8 in the 1915-1924 period to 0.58 in the 1950's (a factor of 41), with the current decade being the fifth worst (a rate of 7.26 per 100,000 so far).

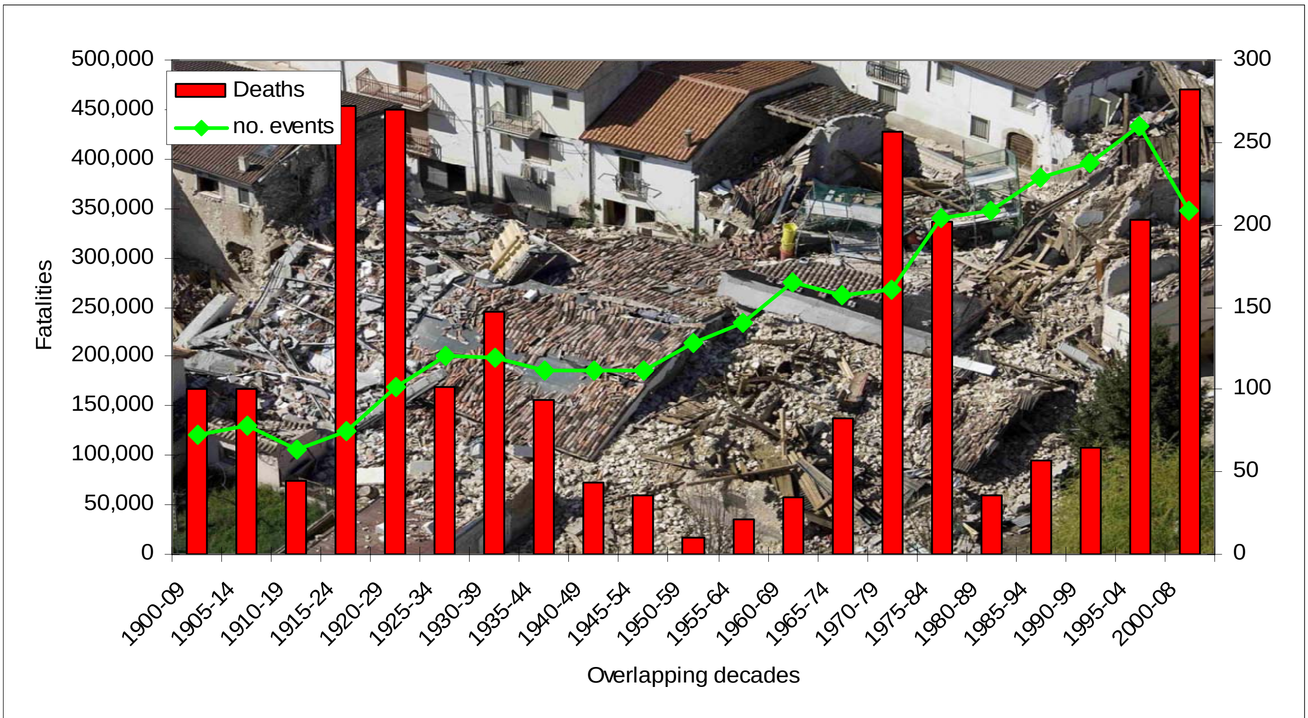

Figure 1 Global earthquake fatalities by decade (1900-2008) and number of catalogued fatal events

In Greece, around 90% of the 1419 deaths reported in 50 fatal earthquakes that took place between 1900 and

2008 were due to building collapse. In the last 40 years (1969-2008) almost 85% of the earthquake-related life losses have been associated with the collapse of reinforced concrete (RC) buildings (out of 271 deaths in 1969-2008, 230 occurred due to the collapse of 35-40 RC buildings), which constitute the largest part of the Greek building stock with respect to built volume, as will be discussed in section 4 of this paper.

3. METHODOLOGY OF SEISMIC VULNERABILITY ASSESSMENT

In this section we will describe the methodologies used by the two groups (RMS and AUTh) as well as the data sources used. The work took place over the October-November 2007 period on a tight time allowance. More research has since taken place to collate Greek earthquake damage survey data from earthquakes of the past 30 years in Greece which will be reported in a forthcoming paper by Pomonis and collaborators.

3.1 Available damage databases

The availability of statistically processed damage data constitutes a fundamental component in seismic vulnerability assessments. The data that were available (and usable) to both co-operating teams were obtained primarily from the following damage databases:

- June 20, 1978 Thessaloniki earthquake: This constitutes currently the most complete damage database with regard to the Greek territory. It comprises 5470 buildings (density of on-site recording 1:2 blocks) located within an area covering nearly half of the central part of the city, and contains detailed data regarding both the buildings' characteristics, as well as damage descriptions and repair costs (Penelis et al. 1986).
- September 13, 1986 Kalamata earthquake: 7101 buildings were analyzed from a total of 10171, classified in one of four categories (green, yellow, red and purple) according to the degree of damage they sustained. This is the only post-earthquake damage database in Greece which employed the additional 'purple' category, used to quantify the buildings which actually collapsed or were so severely damaged that were considered not repairable (OASP 1986-1989; Lekidis et al. 1987, Andrikopoulou 1989).
- June 15, 1995 Aigio earthquake: The database was compiled from the research team of the University of Patras (Fardis et al. 1999) and includes the entire building stock of the Aigio city centre, among which the majority of the damaged buildings from RC and unreinforced load bearing masonry (URM) are found. The database consists of 2014 buildings, of which 857 (42.5%) are URM.
- September 7, 1999 Athens (Mount Parnitha) earthquake: The database was compiled within the framework of a previous research project involving teams from AUTh and ITSAK (Kappos et al. 2007). The collected damage data constitute a representative sample from the region of Ano Liosia (150 building blocks, approximately 10% of the total number of building blocks of the Municipality).
- Damage database from 'Ethniki' Insurance (Ethniki Asfalistiki): This database was compiled as part of the ARISTION research project and comprises 2149 entries (entire buildings or parts of buildings e.g., individual apartments or shops), 96.9% of which are related to the 1999 Mount Parnitha earthquake and 3.1% to the 2003 earthquake of Lefkada Island (YPEHODE-OASP 2005).

3.2 Definition of building typologies

Within the framework of the current research, it was observed that the Greek building stock (mainly concrete, masonry, timber and metal frame) is adequately described by utilizing 6 out of the 33 building typologies suggested by PAGER. However, for RC buildings which constitute the dominant building typology in Greece, it was considered necessary to introduce an additional division of the stock into sub-classes (not necessarily identical for both research teams) based on characteristics which have been shown to influence the seismic vulnerability of structures such as age, height and lateral resistance to seismic actions. In the end, the two teams used slightly different building typologies which are described below in more detail.

3.2.1 RMS Methodology
The methodology followed by RMS was based entirely on empirical damage data from the earthquakes of Kalamata in 1986, Aigio in 1995 and Athens in 1999.

The destructive earthquake of September 13, 1986 (M_W 6.0) that occurred at 20:24 local time in the southern part of Peloponnese, severely hit the city of Kalamata. Its epicenter was located 9 km north of the city. The main event was followed by a number of aftershocks, the strongest of which occurred two days later with a magnitude M5.3 about 1 km east of the city. The main shock resulted in the loss of 20 lives, heavy building damage as well as the collapse of a 22-unit five-storeyed RC apartment block. Several more buildings collapsed during the main aftershock (Anagnostopoulos et al., 1987).

Among the most useful data for the current analysis were those from Kalamata because they provided additional information on the number of buildings that actually collapsed either partially or totally. This is achieved through the addition of an extra class in the typical 3-class (green=suitable to use, yellow=temporarily unsuitable to use, red=unsuitable-dangerous to use) categorization of buildings in conventional post-earthquake damage assessment-building usability surveys. The data from Kalamata are further disaggregated by structural type into RC, URM and mixed load-bearing system buildings (usually older masonry buildings with more recent RC extensions either horizontally or vertically or both), as well as by the number of floors (1 to 7 floors). The data cover 26 neighborhoods of the city and concern 7101 buildings (the total building stock in the city of Kalamata was 10171 and has been entirely surveyed, but the data at neighborhood level have been analyzed before the completion of the entire usability survey which took more than 2 months to complete because there were first-level assessments followed by more detailed second-level assessments especially for buildings that were yellow or red tagged, a common practice in Greek post-earthquake usability assessment surveys). The neighborhood level sub-set allows the assessment of damage in a range of seismic intensities because damage varied substantially within the city due to soil conditions, source and directivity effects due to the causative fault's proximity to the city (Gariel et al., 1991). We have checked the damage distribution by structural type and height of the buildings when using the 7101 buildings neighborhood-level sub-set instead of the city level total of 10171 buildings and have found the distributions to be very similar. Figure 2 shows the damage distribution of buildings per damage state and by structural load-bearing system (buildings of mixed load-bearing systems have been grouped together with those of URM) and the number of floors.

In order to estimate the required collapse probabilities of the various buildings by the structural load-bearing typology, in areas with seismic intensities ranging from VI to IX, it was firstly necessary to assess the intensities experienced in the various neighborhoods of the city. This was achieved through reference to the URM data, because historically intensity scales were developed with exclusive reference to this building typology. Neighborhoods where the number of URM buildings was below 20 were excluded from the assessment, as this was considered to be an insufficient sample to allow for the distribution of buildings into the 4 damage states. In total, seven neighborhoods were excluded and the analysis was carried out with the remaining 19 consisting of 6954 buildings. The assessed seismic intensities per neighborhood are presented in Table 1. It should be noted that the damage data combine the resulting actions of both the main earthquake as well as of the aftershocks. During the aftershocks 3 more RC buildings, as well as many old masonry buildings, collapsed. The average seismic intensity for the 19 neighborhoods was assessed as 9.17 based on the percentage of URM buildings in each neighborhood with regards to the total. This value is in agreement with the assessment by Papazachos and Papazachou (2002) who reported the intensity in the city of Kalamata as IX. The maximum recorded horizontal peak ground accelerations (PGA) were 0.30g and 0.27g in the city centre and in the neighborhood of Nisaki respectively (Anagnostopoulos et al., 1987). The duration of the strong seismic motion in the main event (acceleration>0.10g) was 2.3 seconds. Furthermore, the mean horizontal spectral accelerations for the period 0.1-0.3 sec were 0.84g and 0.62g respectively and the peak horizontal ground velocities (PGV) were 30-40cm/sec.

The number of RC buildings in the 19 neighborhoods were 2950 (1863 had 1 to 2 floors and 1087 had 3 7 floors). Although the data do not include the year of construction, it is known from the 1990 Buildings Census of Greece that in the city of Kalamata the majority (>80%) have been constructed between 1960 and 1983 complying with the 1959 Greek earthquake code. Twenty-six RC buildings were assigned the purple-tag which translates to a partial or complete collapse rate of 0.88% (18 had 1 to 2 floors and 8 had 3 to 7 floors, with respective rates of 0.97% and 0.74%).

Table 1 Estimated macroseismic intensities in 19 neighborhoods of Kalamata during the 1986 earthquake

Neighborhood	Intensity	Number of Buildings
Kordias	<VI	57
Dytiki Paralia, Anatoliki Paralia, Goulimides	VII-VIII	621
Paralia, Aghia Triada	VIII	734
Akrita	VIII-IX	97
Rachi, Athinon, Nisaki, Kolimvitirio, Giannitsanika	IX	2181
Aghia Paraskevi, Aghios Georgios	IX-X	551
Papadakou, Bariamaga, Fytia, Palaia Poli, Kentro	X	2713

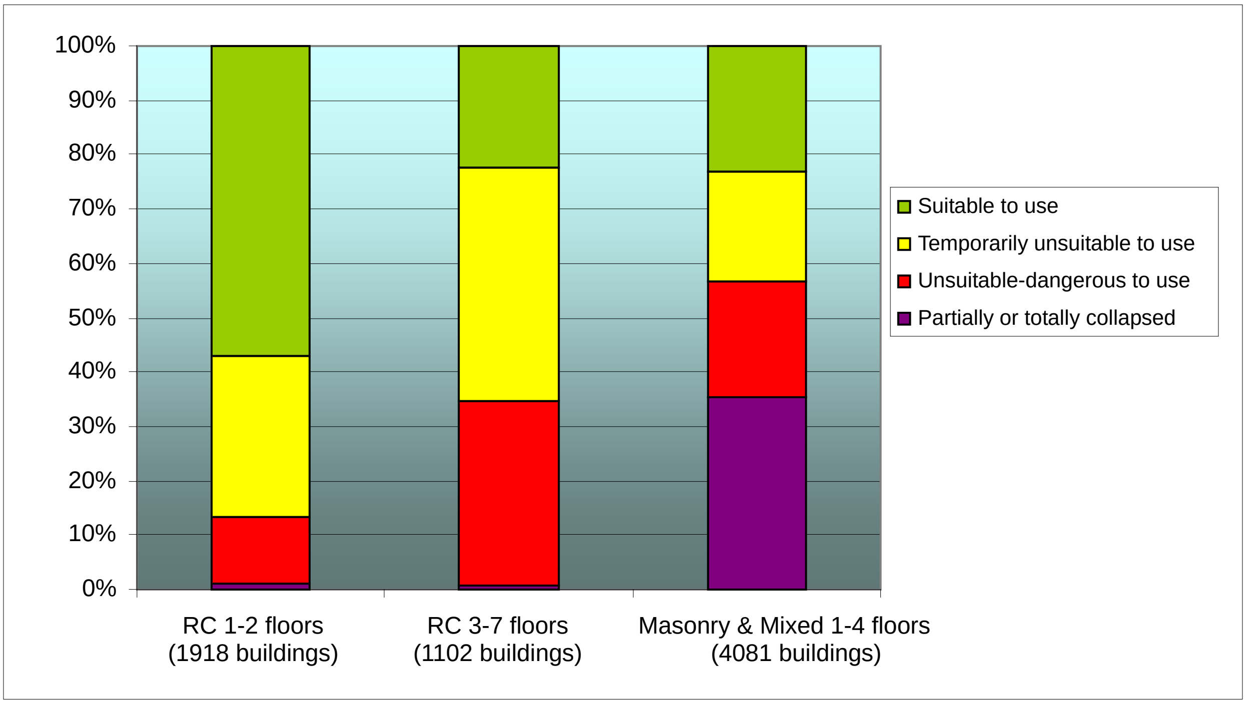

Figure 2 Damage distribution in the city of Kalamata following the 1986 earthquake

Buildings from URM and mixed load-bearing masonry were analyzed both separately and jointly (there were 2959 URM buildings and 1045 buildings with a 'mixed' load-bearing system); in total, 1420 buildings suffered severe damage often deemed to be beyond repair (1231 URM and 189 mixed structure buildings with severe damage rates of 41.6% and 18.1% respectively). However the collapse definition for the purple URM buildings is not the same as the one proposed by PAGER whereby a building is considered to have collapsed when a 50% volume reduction or more has taken place at one or more floors. Typically in Greece URM buildings which are overwhelmingly of the rubble or hewn-stone variety (for more detailed descriptions of URM buildings in Southern Greece see Karantoni and Bouckovalas, 1997) are considered uninhabitable and thus are destined for demolition even when no volume loss has taken place, e.g. a very common damage pattern is the out-of-plane failure of one wall although often the floor or roof above remain in place. Therefore the collapse probabilities for Greek URM buildings proposed hereby are not a good predictor of earthquake casualties. It has been so far not possible to estimate the proportion of URM buildings that have been red or purple tagged in Greece that actually have a volume loss less than 50% in any floor; this is therefore an item for future research. Further analyses were performed for various combinations of load-bearing masonry and neighborhoods. In Figures 3 and 4 the purple-tag percentages for URM, mixed load-bearing buildings and RC buildings (no sub-classes considered) are provided in relation to the assessed seismic intensity (some neighborhoods were aggregated in order to increase the sample size and reduce uncertainty). In general, the purple-tag percentage increases smoothly as the assessed intensities increase, despite the fact that the analysis is based on empirical data and some discontinuities are expected due to the uncertainty in the accurate assessment of the damageability of the seismic action in the various neighborhoods of Kalamata.

In some neighborhoods much higher purple-tag percentages were observed e.g., for the RC buildings in the neighborhoods of Giannitsanika, Akrita, Aghios Dimitrios, Palaia Polis and Kentro the percentages were between 3.5% and 1.9%, or 2.37% in a total of 845 buildings. For the RC buildings there is also reference in the study by Andrikopoulou (1989) which contains the final damage distribution for all the buildings in Kalamata (10171 buildings) but not at neighborhood level, whereby it is reported that the purple-tag percentage of low-rise RC buildings was 1.14% (34 collapses in 2975 buildings) while for the mid-rise (3-7 floors) 0.81% (10 collapses in 1229 buildings) i.e., a little higher than the data used in the current analysis.

Although there were 44 RC and 2220 of URM and mixed structure purple-tag buildings there were only 20 lives lost. Six deaths were caused by the collapse of a 5-storey RC building (the percentage of fatal (deadly) collapses being 0.024% in the total number of RC buildings or 0.081% in the sub-category of high-rise RC buildings), 4 were caused by the collapse of URM buildings (unspecified number), 6 were caused on the streets by falling plaster and walls (mainly due to the collapse of URM) and 4 from other causes (Anagnostopoulos et al., 1987). However, loss of life may have been greater had the earthquake occurred a few hours later (during the time of the earthquake at 20:24 local time many people were gathered at the port of the city in an open space to watch the opening ceremony of a new route which would connect their town to Crete).

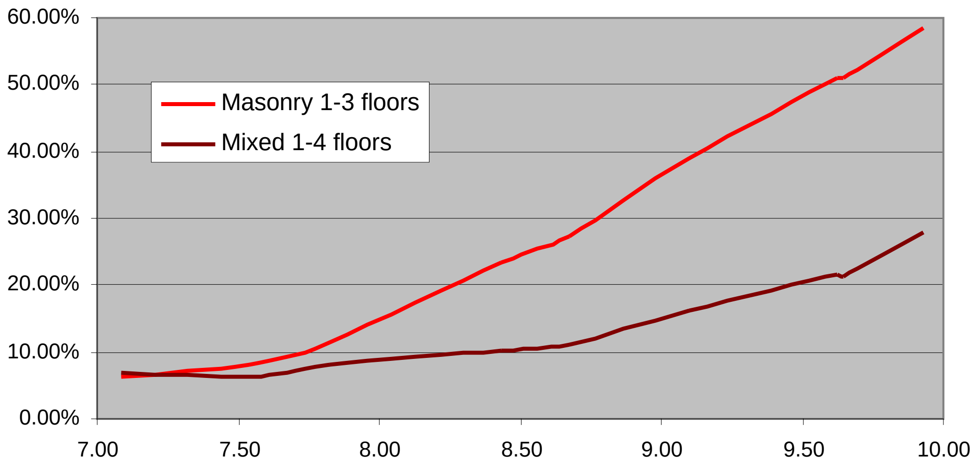

Figure 3 Estimation of collapse probability for URM and mixed URM+RC buildings with respect to the level of seismic intensity using the neighborhood level data from the 1986 Kalamata earthquake

On June 15, 1995 at 03:16 am local time an earthquake of M_s=6.2 occurred 15 km to the east of Aigio city in northern Peloponnese. The damage in the city of Aigio was severe. The data from the 1995 Aigio earthquake refer to 2106 buildings in the city centre (1157 RC and 859 URM buildings) out of the 7200 that existed in the city and its surrounding suburbs at the time of the earthquake (Fardis et al. 1999). Among the major findings of this survey was the better performance of RC buildings constructed after 1984 as well as the uneven spatial distribution of damage with the areas to the north of the Aigio fault (i.e., the coastal zone of the city) exhibiting much less damage in comparison to the city centre. Seismic intensity in the city of Aigio ranged between VII and VIII+. The peak horizontal ground accelerations (PGA) recorded were 0.54g and 0.49g in the city centre (Telecommunications building), while the peak vertical acceleration was 0.20g (Athanasopoulos et al., 1998). The duration of the strong seismic motion (acceleration>0.10g) was 2.5 seconds. The mean horizontal spectral acceleration for the period range between 0.1 and 0.5 sec was very high and reached a value of 0.95g and the horizontal ground velocity (PGV) recorded was 48cm/sec.

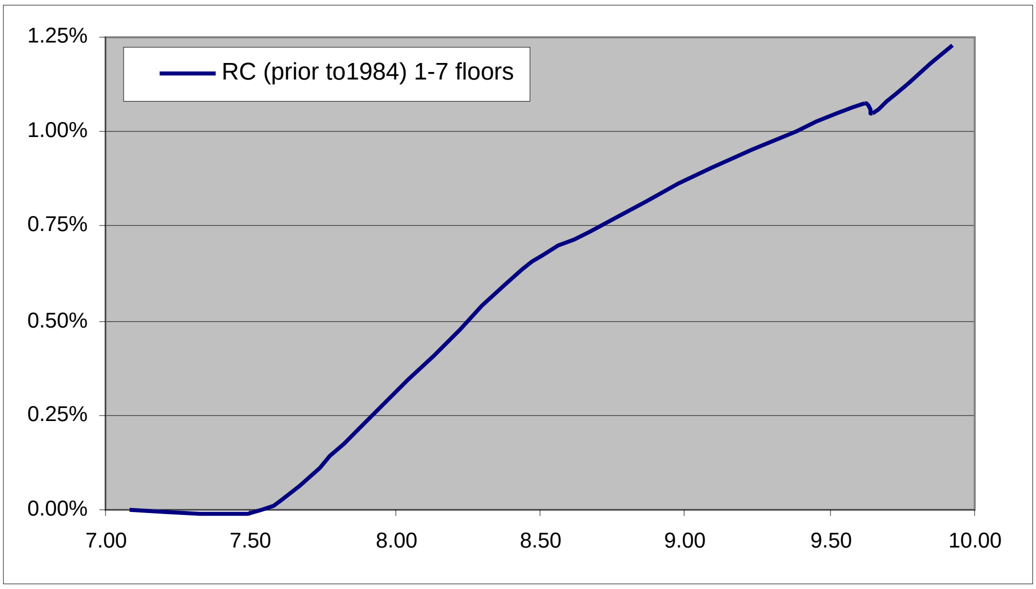

Figure 4 Estimation of collapse probability for RC buildings with respect to the level of seismic intensity using the neighborhood level data from the 1986 Kalamata earthquake

Building collapses occurred in Aigio and 26 lives were lost in 2 multi-storey RC building collapses (Theofili & Vetere Arellano, 2001) one being a 7-storey residential apartment block and the other a 5-storey hotel (10 tourists from France died in this collapse). The number of RC buildings in the city was approximately 4300 (percentage of fatal collapse 0.047%). Higher collapse percentages were observed in a zone 2-3km in length and less than 500m wide situated along a general E-W direction (from the city towards the village of Rododafni) to the north side of the coast of Aigio (Lekkas, 2002) where the 2 RC buildings collapsed and a few more exhibited partial collapse. One more RC building collapsed just outside the city boundary (the administrative centre in a factory complex housing an operation of the Greek Arms Industry) but was thankfully vacant at the time of the earthquake.

As previously mentioned, in the Parnitha 1999 earthquake there were 120 recorded lives lost connected with the collapse of 26 RC buildings (Pomonis, 2002). In the 6 municipalities where the collapses occurred (Ano Liosia, Aharnes, Thracomakedones, Kifissia, Metamorphosis and New Philadelphia) there were 37062 RC buildings (Building Census ESYE-December 2000) i.e. the collapse percentage was 0.070%. Seismic intensity in the 6 municipalities ranged between VI and VIII-IX. The highest intensities were observed in small constrictions where the collapse percentage was higher as was for example the area near the Chelidonou stream. No strong motion instrument existed in the worst-affected areas at the time of the earthquake.

The suggested collapse probabilities for low-rise (1-2 storeys) masonry buildings (URM buildings from stone or solid-brick masonry, typically without mortar and with timber floors as well as URM buildings from cement-block or brick masonry with mortar and RC floors) are in agreement with the findings presented in Figure 3. For RC buildings collapse probabilities are provided for three construction periods (prior to 1961, 1961 to 1995 and after 1995) for low-rise (1-2 floors) and multi-storey buildings (3-7 floors) separately. The suggested probabilities are generally in good agreement with the Kalamata and Aigio observations for buildings constructed prior to 1995. The proposed collapse probabilities are presented in Table 2.

Table 2 Collapse probabilities and population percentages (RMS methodology)

Material or construction type (according to WHE)	Description of construction type	Probability of collapse (%) of building type when subjected to specified shaking intensity				Percentage (%) of population who lives in this building type	
		IX	VIII	VII	VI	Urban areas	Rural areas
16 (a)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built after 1995 (high code). Mid-rise (3-7 floors).	N/A	N/A	0.00	0.00	10.8	6.1
16 (b)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built in 1961-1995 (low code). Mid-rise (3-7 floors).	0.35	0.20	0.00	0.00	62.2	18.9
14 (a)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built prior to 1961 (no code). Mid-rise (3-7 floors).	0.70	0.45	0.17	0.00	7.9	2.0
16 (c)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built after 1995 (high code). Low-rise (1-2 floors).	N/A	N/A	0.00	0.00	2.1	7.1
16 (d)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built in 1961-1995 (low code). Low rise (1-2 floors).	0.40	0.25	0.00	0.00	12.0	22.1
14 (b)	RC MRF with unreinforced clay brick masonry infill-partition walls. Built prior to 1961 (no code). Low-rise (1-2 floors).	1.15	0.75	0.25	0.00	1.5	2.3
23	Steel MRF with unreinforced clay brick masonry infill-partition walls (usually up to 3 floors). 96% after 1990.	N/A	N/A	N/A	N/A	0.0	0.0
29	Wooden (post and beam frame), (usually 1-2 floors)	N/A	N/A	N/A	N/A	0.1	0.3
1	Rubble field stone masonry usually on lime mortar with wooden floors. 90% constructed pre 1960. Usually 1-2 floors.	40.00	21.00	7.00	0.00	1.1	20.6
9	Unreinforced brick masonry usually with cement mortar and RC floors. Mostly pre 1960. Usually 1-2 floors.	16.00	7.00	2.50	0.00	2.3	20.6

Table 2 (continuing)

Material or construction type (according to WHE)	Percentage (%) of working population who works in this building type		Peak average number of occupants per building	
	urban areas	rural areas	Night (residential) urban-rural regions	Day (non-residential) urban-rural regions
16 (a)	11.8	4.6	17.0-24.2	24.0-78.5
16 (b)	49.5	13.2	17.0-24.2	19.4-60.8
14 (a)	6.5	1.0	17.0-24.2	20.4-50.8
16 (c)	2.9	6.8	1.8-1.9	1.9-8.3
16 (d)	12.2	19.5	1.8-1.9	1.5-6.4
14 (b)	1.6	1.6	1.8-1.9	1.6-5.4
23	0.4	0.4	0.0	1.7-7.3
29	0.3	0.5	0.6-1.1	1.6-8.7
1	5.1	23.8	0.6-1.1	1.6-7.9
9	9.7	28.6	0.6-1.1	1.6-8.4

For the purposes of the PAGER project a building is considered to have collapsed when it sustains 50% or more loss of volume in at least one of its storeys. The observations from Kalamata, Aigio and Mount Parnitha earthquakes showed that many buildings which were considered collapsed had a much smaller loss of volume (especially in the case of URM buildings) , a fact supported by the limited loss of life which occurred in very few buildings and the limited number of fatalities linked to the collapse of URM buildings. The final proposed collapse probabilities were thus reduced in order to take this into account.

3.2.2 Aristotle University of Thessaloniki Methodology

Statistical damage data from Greek earthquakes are available, in general, in terms of the classifications used in the first-round (rapid) post-seismic damage inspections – green, yellow, red – and in financial terms (cost of replacement) and only for the 1978 Thessaloniki earthquake (Penelis et al, 1986) and the 1999 Athens (Ethniki Asfalistiki database). Data regarding the buildings that actually collapsed were available only in the Kalamata database. The Aristotle University of Thessaloniki (AUTh) team has developed over the last years a complete set of vulnerability curves for all the common building typologies, mainly reinforced concrete (54 classes) and load-bearing masonry (4 classes), found in Greece (Figure 5). This has been achieved using a 'hybrid' approach which combines statistical damage data with the results from multiple inelastic analyses, both of static and dynamic (only for RC buildings) nature (Kappos et al. 2006, Kappos and Panagopoulos 2009).

It has been observed that most of the available data, although useful per se for the purposes of seismic vulnerability assessments, do not provide satisfactory results with regard to the assessment of collapse probabilities. This is because at the level of intensity where collapse occurs (mostly in the dominating RC class) statistical data, on the one hand, are insufficient, while analytical data on the other hand are in general unreliable (usually too conservative). Therefore, the research effort concentrated on the systematical reprocessing of the available statistical data placing the focus on the differentiation between buildings that collapsed and those that required demolition after an earthquake (most valuable were the data concerning approximately 7000 buildings which were damaged from the 1986 earthquake in Kalamata), as well as the use of the hybrid approach with the subsequently revised statistical data.

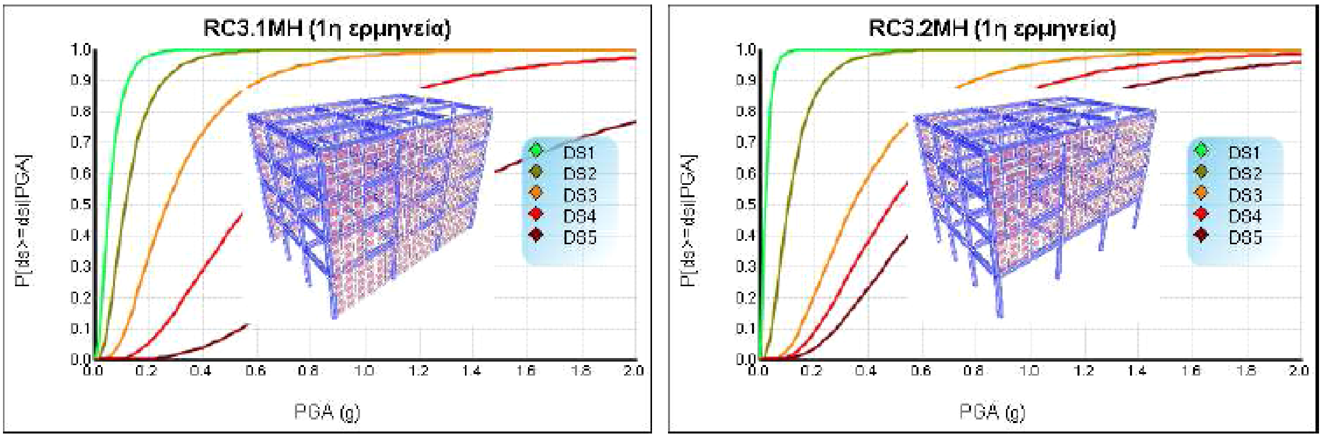

Figure 5 Seismic vulnerability curves for medium-rise RC frame buildings with brick-infill (left) and with pilotis (right) designed according to the latest seismic codes (NEAK/EAK 2000).

Only six out of the 58 building types used by the AUTh research team were considered suitable for this study and were further used in the estimation of collapse probabilities (Tables 3 and 4). From the 54 RC building classes differentiating buildings by age, height, structural system and the existence or absence of masonry infill, only 4 were used differentiating buildings on the basis of their structural system (frame or dual) and their age (buildings designed with the old or new seismic codes). RC buildings which were designed with the 'Additional Clauses' of the 1985 code were considered to exhibit similar behavior with regards to vulnerability with those designed with the new code (NEAK/EAK 2000). Similarly, only two classes were considered for load-bearing masonry buildings differentiating them on the basis of their construction materials (stone or brick masonry) with no further differentiation by height, as was the case in the evaluation of the associated vulnerability curves (Kappos et al. 2006). The aggregation of the various building typologies is due to the fact that the available statistical data and especially those referring to actual building collapses are limited, and further distinctions would require arbitrary assumptions which could in turn lead to unreliable conclusions. For metal frame and timber buildings the AUTh team did not have sufficient statistical or analytical data to evaluate their seismic vulnerability and therefore it was decided to refrain from estimating their corresponding collapse probabilities. As evident from the findings of the RMS team (Table 3) the significance of these buildings in vulnerability studies is very limited (the population percentage residing or working in such buildings is in total less than 1%).

The procedure followed for the estimation of collapse probabilities for every building typology and for the intensity range between VI and IX comprises two stages. Firstly, the probability that the buildings have sustained damage levels ranging from 'heavy damage' to 'collapse' is estimated in one of the following ways:

- From the number of buildings classified as 'red' in the available damage databases, in case where sufficient data exist for the concerned building typology (it should be reminded that in all the available damage databases, with the exception of the Kalamata database, there is no distinction between the number of buildings with heavy damage and those that actually collapsed)
- From the available vulnerability curves (Kappos et al. 2006, Kappos & Panagopoulos 2009) the probability that the peak ground acceleration (PGA) corresponding to every intensity level has exceeded the value of PGA corresponding to damage level 4, (representing the degree of 'heavy damage' (P[ds>ds4|PGA]) is evaluated assuming that damage state 4 and 5 represent the state of buildings when classified as red. Vulnerability curves have been developed for 54 RC and 4 URM building typologies and therefore for this study average curves are evaluated from the relevant typologies that can be aggregated into more generic classes (e.g., RC frame buildings designed to old seismic codes).

The next stage involves the evaluation of the number of buildings which actually collapsed (purple), using mainly the available data from the Kalamata database, in terms of the sum of the buildings which sustained damages ranging from 'heavy' to 'collapsed' for each one of the studied building typologies.

Table 3 Collapse probabilities and population percentages (AUTh methodology)

Material or construction type (according to WHE)	Description of construction type	Probability of collapse (%) of building type when subjected to specified shaking intensity				Percentage (%) of population who lives in this building type	
		IX	VIII	VII	VI	Urban areas	Rural areas
16	RC MRF building designed with old codes	1.00	0.35	0.10	0.05	50.0	25.0
16	RC MRF building designed with new codes	0.40	0.10	0.05	0.00	7.5	9.0
19	RC dual system building designed with old codes	0.75	0.25	0.10	0.01	12.5	3.0
19	RC dual system building designed with new codes	0.35	0.05	0.01	0.00	22.0	9.0
1	Stone masonry buildings	55.00	10.00	5.00	3.00	1.5	23.0
9	Unreinforced brick masonry buildings	7.50	1.00	0.10	0.00	5.5	30.0

It was considered useful to present additionally a second approach according to which collapse is defined on a financial basis. In this case, a building is assumed to be 'collapsed' when it has sustained such a high level of damage whereby its replacement is deemed to be more economical than its repair. Such an approach is of great significance when vulnerability studies aim to facilitate the financial management of seismic risk and not the estimation of human casualties (as required for the PAGER project). The procedure followed in the second approach is similar to the first one, with the main difference being that the estimated collapse probabilities refer to RC buildings which sustained damage level 5 (ratio of repair cost over replacement cost > 60%) or damage level 4 for URM buildings (ratio of repair cost over replacement cost > 50%). The results are shown in Table 4.

Table 4 Collapse probabilities (financial basis approach – AUTh methodology)

Material or construction type (according to WHE)	Description of construction type	Probability of collapse (%) of building type when subjected to specified shaking intensity			
		IX	VIII	VII	VI
16	RC MRF building designed with old codes	15.00	5.00	2.00	0.50
16	RC MRF building designed with new codes	4.00	0.50	0.02	0.00
19	RC dual system building designed with old codes	11.50	3.00	0.15	0.00
19	RC dual system building designed with new codes	3.00	0.30	0.01	0.00
1	Stone masonry buildings	80.00	14.00	8.00	5.00
9	Unreinforced brick masonry	37.00	4.00	0.60	0.20

4. ESTIMATION OF THE POPULATION LIVING OR WORKING IN EACH BUILDING TYPOLOGY

The percentage of the population living or working in each building typology was determined through systematic processing of the building and population census data provided by ESYE (National Statistical Service of Greece) in 2001 as well as their projections to 2007 (these data are fundamental for determining loss of life). The ESYE data are provided separately for both urban and rural areas allowing, thus, the separate estimation of the above for each regional type and in turn the detection of any significant differences.

According to the RMS team, for example, it was estimated that 41.2% of the rural population and 52.4% of the rural working population is found in URM buildings, while in the urban areas (75.1% of the total population and 77.1% of the total working population) 87.2% of the population and 76.4% of the working population is found in RC buildings constructed after 1961. The peak average number of occupants by structural and regional type for residential buildings was estimated from the population data, assuming a hypothetical time of earthquake occurrence at 2 a.m. (when it was assumed that all residents are at home), while the peak average number of workers by structural typology for the buildings used for work purposes was estimated from the data regarding the labor force (the number of pupils, students, soldiers, visitors, hospital patients etc. was also included as part of the labor force) assuming a hypothetical time of earthquake occurrence at 2 p.m. (when it was assumed that all workers occupy the buildings they work). Therefore, it was estimated that on average there is only 0.6 people per building in residential URM buildings in rural areas, while in a 3-11 storey RC building constructed between 1996 and 2006 used for work purposes and located in an urban area there are on average 78.5 workers. The estimations for the distribution of the urban and rural population and labor force in Greece as well as the peak average number of occupants in a residential building or workers in a 'working' building for each building typology are presented in Table 2.

The AUTh team followed similar assumptions for the population distributions, but for the distribution of buildings according to their ability to resist seismic actions it was assumed that in urban areas 80% of the buildings designed before 1985 have a frame structure and 20% a dual system, while for buildings constructed after 1985 the corresponding percentages are 35% and 65% respectively. For rural areas it was assumed that 90% of the buildings designed before 1985 have a frame structure and 10% a dual system, while for buildings constructed after 1985 the corresponding percentages are 60% and 40% respectively. Furthermore, additional assumptions were made based on the data available through the Thessaloniki and Athens databases (Ano Liosia and Ethniki Asfalistiki database) in terms of the average floor area for each building typology (buildings of dual system are typically larger than frame buildings). The results of the analysis are presented in Table 3. The fields for which the team did not have the necessary data required for the estimation of the corresponding values were left blank (following the instructions by the PAGER team). These fields are however covered by the RMS submission.

5. RESULTS-COMPARISONS WITH OTHER COUNTRIES

The results of the analyses performed by the two teams, as discussed above, are presented in Table 2 (RMS) and Table 3 (AUTh). The level of agreement in the results provided by the two teams is satisfactory, which was somewhat expected given that the primary data used by both teams were identical (available damage databases), although the methodologies were fundamentally different.

The results from various other countries are already available through PAGER and it is therefore of great interest to compare them with the Greek results. Figures 5 and 6 compare the probabilities of collapse for stone masonry and RC buildings respectively, with the results from 14 countries which in their majority are characterized as zones of high seismic risk, although there are countries (such as Germany, France and Switzerland) of low to medium seismic risk.

A large spread is observed in the submitted results regarding the probability of collapse (but also among the building typologies present in each country which are not shown in the figures). This is somewhat expected given differences in the construction types found in each country as well as differences in their economical and social status (for example the probabilities of collapse of stone masonry buildings are far greater in countries such as India, Pakistan and Peru in comparison to countries such as France, Germany and Greece as shown in Figure 6). However, to a large extent the observed spread (especially for RC buildings, shown in Figure 7) is the effect of the different methodologies adopted for the estimation of collapse probabilities by experts in each country, since no specific guidelines were provided with regard to the procedure to be followed in estimating such probabilities. It is obvious to the authors of this paper that the particularly high collapse probabilities suggested by some country experts (e.g., India, Pakistan, but also Cyprus for URM buildings) have not been estimated following the strict assumption regarding collapse as previously mentioned, but include buildings which have sustained heavy damage and may have been demolished at a later stage. An additional reason for the observed spread is the classification of buildings into typologies which may vary from country to country. For example, as shown in Figure 7, the probabilities of collapse for buildings with RC shear walls in Chile are zero for all intensities apart from IX (where collapse probabilities are 1%) which are known to behave better than frame structures (for which no probabilities are provided).

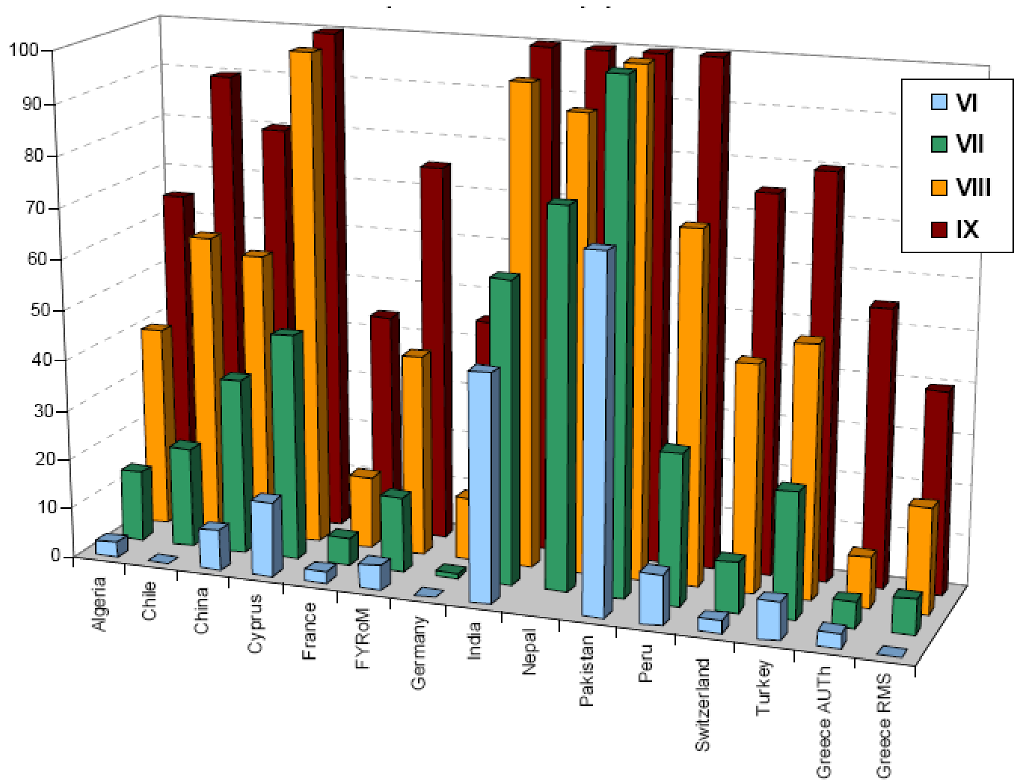

Figure 6 Collapse probabilities in the intensity range VI to IX for unreinforced stone masonry buildings as provided by the experts solicited by EERI in various countries.

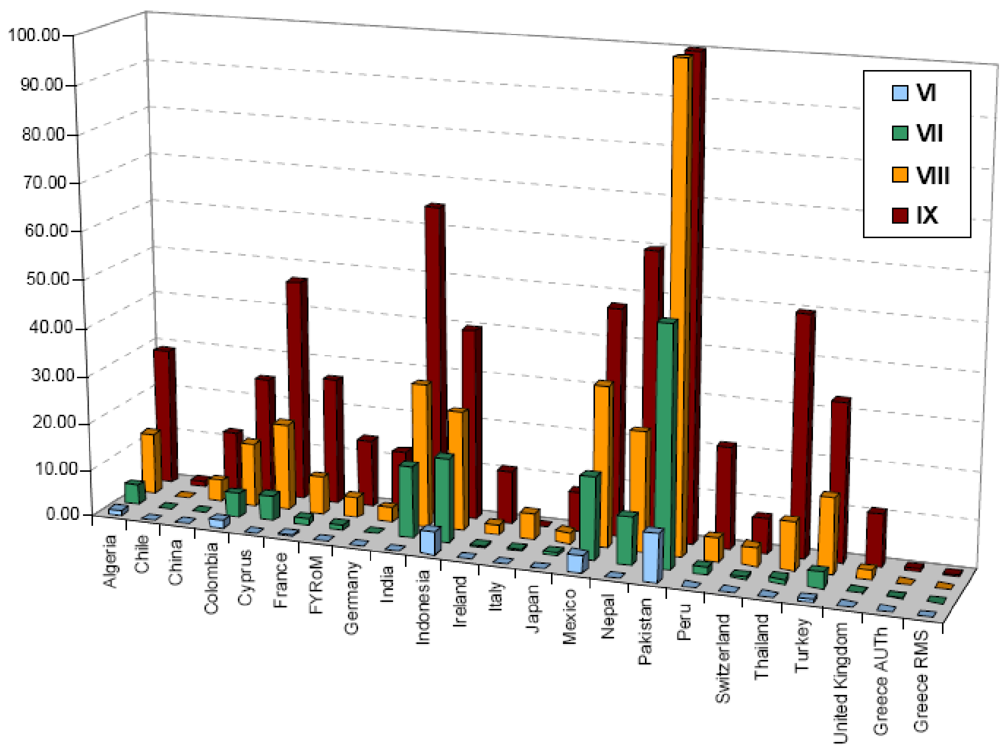

Figure 7 Collapse probabilities in the intensity range VI to IX for reinforced concrete buildings as provided by the experts solicited by EERI in various countries.

It should be noted that in the last 30 years (1978-2007) approximately 6000 buildings have been 'red-tagged' in Greece during extensive post-seismic damage assessments in the various earthquake-struck areas. Loss of life, however, has only occurred in 40-45 buildings. The three earthquakes of Kalamata, Aigio and Parnitha were of magnitude 5.9-6.1 with an extremely limited duration of the strong motion (less than 5 sec) at a relatively short distance from urban centers. The estimations presented here have been made on the basis of strict assumptions as to what constitutes building collapse, in relation to the up-to-date experience in Greece, which shows that loss of life has only occurred in a limited number of collapses.

Larger collapse percentages are expected in earthquakes of larger magnitudes and longer duration, whereby seismic intensity may exceed IX or X. For example, in the 1995 Kobe earthquake, where intensity reached X-XI, the percentages of total or partial collapse for RC buildings were of the order of 5% (DPRI, 1995) in the Chuo ward (city centre). The percentage of collapse for RC buildings constructed prior to 1981 (when the seismic building code of Japan was upgraded) were 15% in Sannomiya located in the Chuo ward, as recorded in the detailed assessment carried out by one of the authors of this paper (EEFIT, 1997). In Sannomiya, the peak horizontal ground accelerations (PGA) recorded were 0.62g-0.82g with peak velocities (PGV) 60-120cm/sec, while the duration of the strong motion (acceleration>0.10g) exceeded 15sec.

Finally, it should be noted that an additional factor leading to the observed differences among international findings is the correspondence between intensity and acceleration (e.g., in the hybrid methodology of AUTh the analyses are performed for successively increasing values of acceleration in the used records). Table 5 shows the values of the peak ground acceleration (PGA) as computed from the relationship proposed by Koliopoulos et al. (1998) and used in the analyses of AUTh as well as the range of values adopted in the PAGER project (based primarily on American experience). The largest differences are observed in the lower intensities for which the Greek values lie far from the mean (or in cases outside) of the range of values of the PAGER project.

Table 5 Correspondence of Intensity (I) and peak ground acceleration (PGA) with various assumptions

I	PGA (Koliopoulos et al., 1998)	PGA (WHE PAGER form)
VI	0.089g	~0.092-0.18g
VII	0.187g	~0.18-0.34g
VIII	0.391g	~0.34-0.65g
IX	0.820g	~0.65-1.24g

6. CONCLUSIONS

Estimations of building collapse probabilities due to earthquakes (which is directly related to loss of life as well as economic losses) for all common building typologies found in Greece were presented in this paper (for the first time), together with estimations of the population percentage that lives or works in each building typology (of fundamental importance in the determination of loss of life).

Two methodologies were used for the estimation of collapse probabilities for each building typology for the most common macroseismic intensities (VI to IX); one based exclusively in the statistical processing of damage data from Greek earthquakes and one utilizing hybrid (analytical and empirical) vulnerability curves developed by the AUTh research team. The results were compared to those from various other countries, both of high and low seismic risk, geographically covering four continents.

As expected, it was confirmed that the available statistical data, although valuable, do not allow for the differentiation of many building typologies while the values of the collapse probabilities do not always exhibit the expected change with respect to seismic intensity. Furthermore collapse probabilities are sensitive to the assumptions made for statistically processing damage data and for the utilization of vulnerability curves. The difficulty in estimating collapse probabilities is that estimations are based on a very small number of collapsed buildings, which differs significantly from the (usually available) number of buildings exhibiting heavy damage (red tag) and which may be demolished after an earthquake. The insufficiency of statistical data, in addition to the uncertainty in the distinction between buildings which actually collapsed to those which were heavily damaged are among the main reasons that explain the considerable differences observed when comparing the results of this study with those from a total of 14 countries. Furthermore, the differences in building quality among the various countries should not be overlooked.

The current study constitutes an initial attempt to estimate building collapse probabilities based on expert opinion and was completed within a limited time frame that did not allow for more detailed analyses. Further in-depth analyses regarding the various assumptions made, e.g., the choice of seismic intensity in earthquake struck areas, the correspondence of seismic intensities with acceleration and velocity parameters (ground and spectral) as well as with other parameters used to describe strong motion ‘damageability’ will provide greater reliability and accuracy to the estimations and will facilitate the development of scenarios to be used for improved preparedness and mitigation actions against seismic risk in Greece.

7. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Earthquake Planning and Protection Organization of Greece (OASP) and the Institute of Engineering and Earthquake Resistant Construction in Thessaloniki (ITSAK) for kindly providing seismic vulnerability data for buildings in Greece as well as to EERI and USGS who are responsible for the PAGER project.

REFERENCES

Allen, T.I., Marano, K.D., Earle, P.S. and Wald, D.J. (2009). PAGER-CAT: a composite earthquake catalog for calibrating global fatality models. *Seismological Research Letters*, V. 80, No. 1, January/February 2009.

Ambraseys, N.N. (2004). The 12th century seismic paroxysm in the Middle East: a historical perspective. *Annals of Geophysics*, V. 47, No. 2/3, April/June 2004.

Anagnostopoulos, S. A., Rinaldi, D., Lekidis, V.A., Margaris, V.N. and Theodulidis, N.P. (1987). The Kalamata, Greece, earthquake of September 13, 1986. *Earthquake Spectra*, V. 3, No. 2, pp. 365-402.

Andrikopoulou, K. P. (1989). Damage assessment from the earthquakes of Kalamata on 1986 – Correlation of damage distribution with soil conditions in Kalamata: national report. *Bulletin of the International Institute of Seismology and Earthquake Engineering*, Japan, V. 23, 169-188.

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 the *Proceedings of the 11th European Conference on Earthquake Engineering*.

Coburn, A. and Spence, R. J. S. (2002). *Earthquake Protection* (2nd edition), Wiley, Chichester.

DPRI (1995). *Preliminary report on the Great Hanshin earthquake of January 17, 1995*. Disaster Prevention Research Institute, Kyoto University, Special Issue, February 1995.

EEFIT (1997). *The Hyogo-Ken Nanbu Earthquake of 17 January 1995*. Report of the U.K. Earthquake Engineering Field Investigation Team. The Institution of Structural Engineers, London, 1997.

Fardis, M.N., Karantoni, F.B. and Kosmopoulos, A. (1999). *Study and statistical processing of the damages from the 15-6-95 Aigio earthquake*. Final report to OASP.

FEMA-NIBS (2003). *Multi-hazard Loss Estimation Methodology - Earthquake Model: HAZUS®MH Technical Manual*, Washington DC.

Gariel J.-C., Bard P.-Y., Pitilakis K. (1991) A theoretical investigation of source, path and site effect during the 1986 Kalamata earthquake (Greece). *Geophysical Journal International*, V.104, pp. 165–177.

Kappos, A.J., Lekidis, V., Panagopoulos, G., et al. (2007). Estimation of economic loss for buildings in the area struck by the 1999 Athens earthquake and comparison with actual repair costs, *Earthquake Spectra*, V. 23, no. 2, 333-355.

Kappos, A. J., Panagopoulos, G., Panagiotopoulos, Ch. and Penelis, Gr. (2006). A hybrid method for the vulnerability assessment of R/C and URM buildings, *Bulletin of Earthquake Engineering*, V. 4, No. 4, 391-413.

Kappos, A.J. and Panagopoulos, G. (2009). Fragility curves for reinforced concrete buildings in Greece, *Structure and Infrastructure Engineering*, In press, doi:10.1080/15732470802663771.

Karantoni, F. V. and Bouckovalas, G. (1997). Description and analysis of building damage due to Pyrgos, Greece earthquake. *Soil Dynamics and Earthquake Engineering*, V. 16, 141-150.

Koliopoulos, P. K.; Margaris, B. N.; Klimis, N. S. (1998). Duration and energy characteristics of Greek strong motion records, *Journal of Earthquake Engineering*, V. 2, no. 3, 391-417.

Lekidis B., Papaioannou Ch., Leventakis G., Tsokas G., Kyratzi A., Zacharopoulos S., (1987). *Isoseismals of the Kalamata earthquakes*. Research project appointed by OASP (29/10/1986) to ITSAK and the Geophysics Laboratory of AUTh.

Lekkas, E.L. (2002). The role of earthquake-related effects in urban complexes, *Natural Hazards*, V.25, p. 23-35.

OASP (1986-1989). Inventory of research studies concerning the Kalamata earthquake.

Papazachos, B. and Papazachou, K. (2003). *The earthquakes of Greece*, Ziti Publications, Thessaloniki (in Greek).

Penelis, G. et al. (1986). *Statistical evaluation of the damages caused by the 20-6-78 earthquake to the buildings of Thessaloniki*. Research project AUTh-YASBE-OASP, Thessaloniki (in Greek).

Pomonis, A. (2002). The Mount Parnitha (Athens) Earthquake of September 7, 1999: A Disaster Management Perspective, *Natural Hazards*, Vol. 27, 171-199.

Spence, R. (2003). Earthquake risk mitigation in Europe: progress towards upgrading the existing building stock. *Proceedings of the 5th National Conference on Earthquake Engineering of Turkey*. Invited Lecture.

Theofili, Ch. and Vetere Arellano A. L. (eds.) (2001). *Lessons Learnt from Earthquake Disasters that occurred in Greece*, Natural and Environmental Disaster Information Exchange System (NEDIES Project), EUR Report 19946 EN, JRC Ispra.

YPEHODE-OASP (2005). Development of a database and processing of the data collected from the studies regarding the reinstatement of the earthquake affected. Logismia Athens.