Framework for the derivation of fragility curves for deficient buildings using EC8 damage levels and Risk Mitigation for Cyprus.

N.C. Kyriakides, C.Z. Chrysostomou
Cyprus University of Technology, Cyprus

SUMMARY
The quantification of the devastating effects from earthquakes on buildings can be achieved with the use of earthquake risk assessment. The formulation of strategies to minimize this risk is a complex task which relies on data regarding mainly the hazard, vulnerability and remaining life of the buildings. In this paper the case study of Limassol municipality is presented. Initially the building inventory and categorization is defined followed by the selection of hazard scenarios and the development of analytical vulnerability curves. In the final part, risk assessment is performed leading to the formulation of retrofitting strategies for sustainable use.

Key words: Earthquake Risk Assessment, fragility curves, life expectancy, risk mitigation.

1. INTRODUCTION

Since the beginning of civilisation, millions of people and thousands of structures around the world have perished in earthquakes. Unfortunately, short-term earthquake prediction is still impossible. However, there are methods available for the approximate long-term prediction of earthquake events. Earthquake risk assessment (ERA) is necessary to develop risk management strategies (RMS) usually used to mitigate the undesirable results of seismic actions. The mitigation is achieved through strengthening of the existing building stock to avoid undesirable damage on the buildings within a predefined time framework (remaining life of a building).

The island of Cyprus, which is situated in the Eastern Mediterranean region, lies within the second largest earthquake-stricken zone of the earth. Throughout its history it has suffered significant damage due to earthquakes. Since 1995, 3 major earthquakes, with magnitude Ms > 5.7 have hit the island, causing two deaths, injuries, severe structural damage and economic losses. This has increased concern amongst the people of Cyprus and highlighted the need for improved risk assessment and management. The first basic seismic provisions were introduced in 1986. In 1994 a formal and comprehensive aseismic code was introduced in the island (CCEAA, 1994).

In order to examine the seismic risk of the existing building stock of the island it was decided to use the municipality of Limassol as a case study. The decision was made based on the fact that it is situated at the southern part which has proven to be of higher risk due to its proximity with the Cyprian Arc. In addition, most of the buildings were constructed prior to the enforcement of the aseismic code, which is the case for all the tall buildings (>6 floors), with the use of low strength concrete and very low ductility reinforcement. The district of Limassol is shown with the red line in Figure 1.1, whereas the borders of the Limassol municipality, which is the case study area, is shown with the black line. The spatial distribution of buildings in the municipality is shown in Figure 1.2. It is observed that it comprises of a very dense building stock concentrated close to the coastal line.

Figure 1.1. Satellite image of Cyprus (the district of Limassol with red line the municipality with black line).

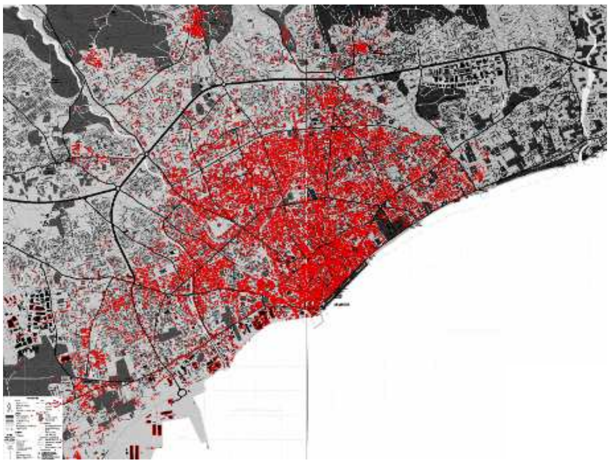

Figure 1.2. Distribution of buildings in Limassol municipality

2. COMPILATION OF THE BUILDING STOCK

The first task for ERA is the compilation of the building inventory which should include the number of buildings and their categorization based on parameters such as their height, year of construction, material etc., that affect their vulnerability. For the area under study, the data resources available were the Statistical Service Department of Cyprus and the archives of the local municipality.

The initial approach towards obtaining inventory data was by using the data in the Census of Population that includes information on the existing building stock. The available information regarding our project was found in two tables. Table 15 of volume 3 includes the number of houses (≤ 2 floors) and apartments per district and urban/rural areas and Table 9A of volume 2 includes the number of living quarters per municipality and community and per urban/rural areas. The extracted data for the case study area are shown in Tables 2.1 and 2.2 below.

Table 2.1. Number of houses and apartments in Limassol district (urban)

	1946-1960	**1961-1970**	**1971-1980**	**1981-1990**	**1991-1995**	**1996-2001**	**2001-2011**
Houses	4221	5725	9973	12345	5550	4583	14986
Apartments	341	1057	4267	7135	2912	1683	13674

Table 2.2. Number of living quarters in the district of Limassol (urban).

Geo. Code	Name	Living Quarters						
		1946-60	**1961-70**	**1971-80**	**1981-90**	**1991-95**	**1996-2001**	**2001-2011**
5000	Limassol municipality	3907	5402	8984	10673	3676	3063	3773
5011	Mesa Geitonia	256	665	1166	1190	849	539	496
5012	Agios Athanasios	58	98	1087	735	629	547	1237
5013	Germasogeia	50	107	819	2094	1021	754	1627
5020	Pano Polemidia	1	24	627	424	78	74	13
5021	Ypsonas	104	124	328	500	330	444	804
5022	Kato Polemidia	171	337	937	2706	940	674	971
5120	Mouttagiaka	27	12	47	343	243	238	370
5124	Agios Tychonas	35	30	300	997	559	125	550
5125	Parekklisia	26	38	46	108	286	167	628
5127	Monagroulli	14	17	25	37	39	44	13
5128	Moni	10	13	14	44	27	39	159
5129	Pyrgos	34	46	84	179	138	119	863
5202	Tserkezoi	6	0	7	3	1	2	0
District of Limassol (Urban)		4699	6913	14471	20033	8816	6829	11504
Limassol Municipality		83%	78%	62%	53%	42%	45%	33%

Using the number of living quarters in Table 2.2 for the whole of Limassol district it was possible to calculate the corresponding percentage of Limassol municipality (case study area) per time period. These percentages were then applied to Table 2.1 values to estimate the number of houses and apartments in Limassol municipality per time period (Table 2.3).

Table 2.3. Number of houses and apartments in Limassol municipality

	1946-1960	**1961-1970**	**1971-1980**	**1981-1990**	**1991-1995**	**1996-2001**	**2001-2011**
Houses	3510	4474	6192	6577	2314	2056	4945
Apartments	284	826	2649	3801	1214	755	4512

Based on the estimated data for the municipality it was observed that nearly 70% of the existing building stock lacks any seismic design based on the fact that the first aseismic code in the island was enforced in 1994 (CCEAA, 1994).

A further categorization of the houses took place based on the data of the Census regarding the number of rooms per house. It was found that the vast majority (65%) of houses are of two floors. Therefore it was decided to examine the earthquake risk related with this building category (referred to as low-rise in the remaining paper).

Regarding the high-rise buildings, additional data were obtained by examining the database of the building permits issued by the municipality. It was found that approximately 200 buildings have an average of 7 floors. This was chosen as the 2nd building category due to its high vulnerability and it will be investigated in detail in order to determine its risk. Detailed drawings for 2 existing typical buildings, one for each category, were selected from the municipality's archives to be used as prototypes for each category. Based on their plan characteristics, material strengths and cross-section dimensions, two mathematical models were formed using the ANSRuop software that was developed at the University of Patras. The mathematical model for the high-rise building is shown in Figure 2.1.

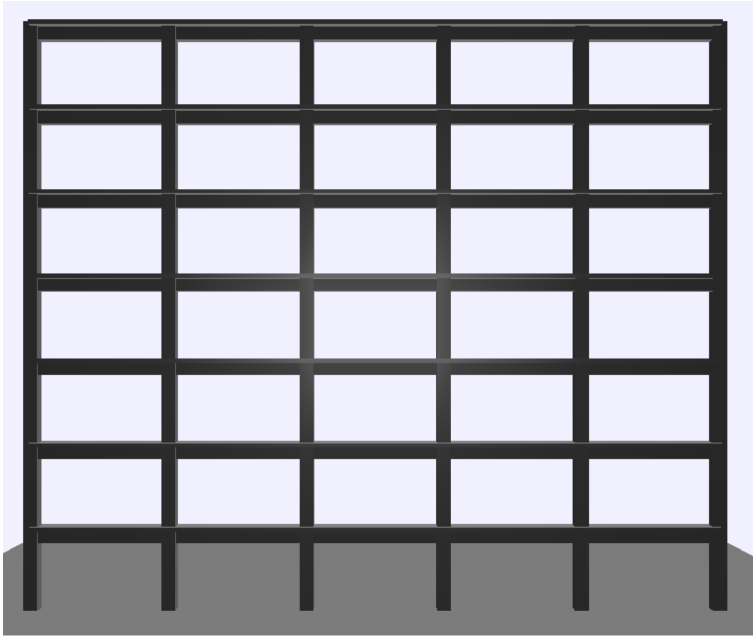

Figure 2.1. Mathematical model of high-rise building in ANSRuop

3. SEISMIC HAZARD

The determination of the seismic hazard of the area under consideration was achieved primarily with the use of the Microzonation Study of the city of Limassol (CGSD, 2000). The study concluded that the municipality is divided into 2 seismic zones. Zone I is along the seafront where high-rise buildings are located, and Zone II covers the inner part of the municipality where the construction is dominated by houses (Figure 3.1). For each zone a response spectrum was drawn differing in the length of the plateau (Figure 3.2). Based on the 2 spectrums, 7 sets of time-history records were derived which were used for the determination of analytical fragility curves as described later in the paper.

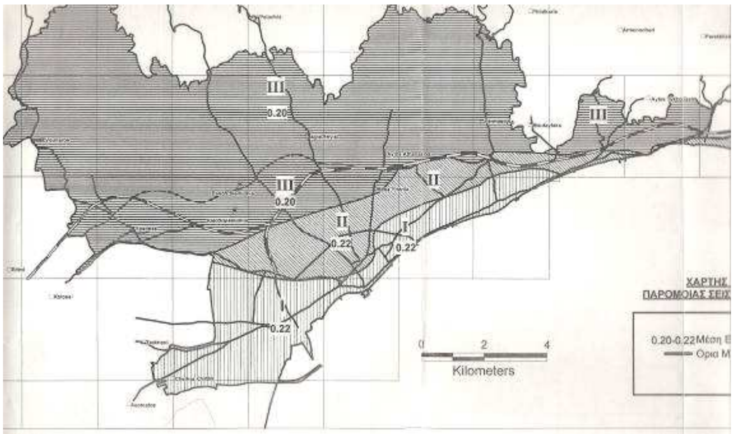

Figure 3.1. Seismic zonation of Limassol municipality based on the Microzonation study

In order to proceed to risk assessment calculations it is vital to determine the frequency of occurrence of seismic events in the area under consideration. The importance of this information lies on the fact that, unlike new buildings, a specific life span does not exist for existing buildings. The owner should be able to define their remaining life based on the period of construction, their use etc. To assist his decision, the earthquake risk needs to be defined for a variety of return periods. When the return period is chosen, the engineer should design his retrofit strategies based on the corresponding PGA. After a wide literature search it was found that the guideline for strengthening of existing public buildings in Cyprus prepared by the Ministry of Interior addresses this issue and proposes three return periods and the corresponding seismic hazard scenarios shown in Table 3.1. Each of the three hazards has 10% probability of exceedance in the specified remaining service life.

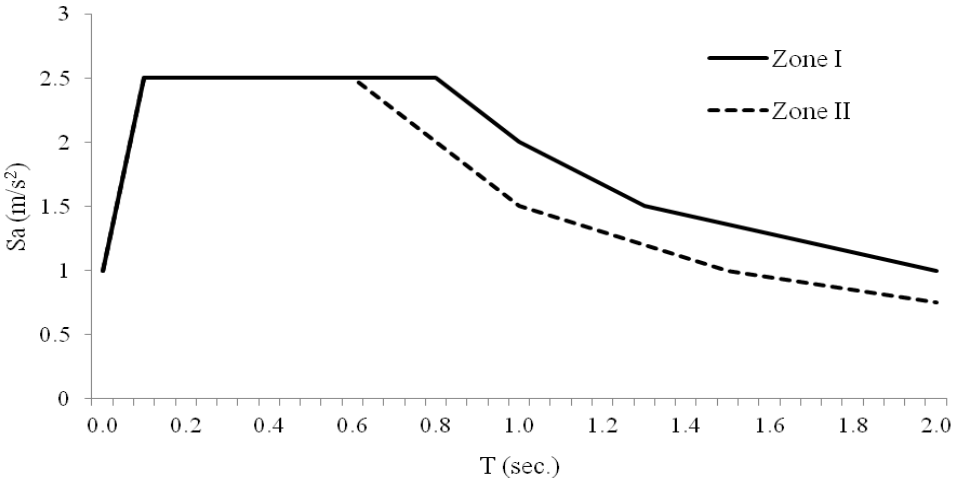

Figure 3.2. Response spectra for the two seismic zones in Limassol municipality

Table 3.1. Seismic hazard scenarios

Remaining Service life	10 years	20 years	50 years
Acceleration (g)	0.125	0.175	0.250

4. SEISMIC VULNERABILITY

In the absence of any reliable analytical vulnerability curves and due to the very low number of empirical damage data from previous earthquakes in the island, it was decided to derive new analytical vulnerability curves for the selected building categories. After a wide literature search it was concluded that these curves should be probabilistic and that the use of time-history analysis would provide the benefit of accounting as well for variations in the hazard, through the use of a number of records for each hazard level. In addition, it was concluded that the damage levels proposed in EC8-Part3 (CEN, 1998) for the assessment of existing RC structures should be used for the derivation of the fragility curves. The framework for the derivation of these curves is shown in Figure 4.1 and it is described in detail in the following paragraphs.

As it was mentioned before, 2 simulation models (low-rise, LR and high-rise, HR) were created based on the corresponding chosen prototype buildings. This simulation models lack any seismic design and are referred to as OLD (O) in the rest of the paper. In order to assess the improvement in the performance of the newly designed buildings of the same categories, the same simulation models were also designed based on Eurocode 8 (1998). These models are referred to as NEW (N) in the rest of the paper. The design load combinations for both old and new models are shown in Table 4.1. The design characteristics of the models are shown in Table 4.2.

Table 4.1. Design combinations for the design of the simulation models.

Load Combination	G_k (Dead Load)	Q_k (Live Load)	Horizontal Load
No seismic design	1.4	1.6	-
(OLD)	1.2	1.2	±1.2 (0.2 KN/m^2)
Full seismic design	1.35	1.5	-
(NEW)	1	0.3	Design Spectrum of EC8 (CEN 1998-1)

Table 4.2. Details of frame members (from design)

Building category		Columns	Beams
LRO	Dimensions	250X250	250X500
	Reinforcement	4Φ16	3Φ14+3Φ14
LRN	Dimensions	250X500	250X500
	Reinforcement	10Φ18	4Φ14+4Φ14
HRO	Dimensions	400X400	250X500
	Reinforcement	12Φ18	3Φ16+3Φ16
HRN	Dimensions	500X500	300X600
	Reinforcement	12Φ20	6Φ20+4Φ20

In order to account for variations in buildings of the same category, key parameters such as material strengths, f_{cm} and f_y for concrete and steel, respectively, spacing of stirrups at column ends, *S*, and lap length of column bars, *L*, affecting the response of these models were treated probabilistically using the Latin Hypercube Technique to increase the number of the simulation models for each category (15 for each category) and thus increase the accuracy of our results. The probabilistic parameters used and their corresponding probabilistic distribution functions are shown in Table 4.3.

Table 4.1. Probabilistic parameters used for the derivation of simulation frames

Propabilistic Parameter	No seismic design		Full seismic design	
	Average	St.Deviation	Average	St.Deviation
$\mathbf{f_{cm}}$	24	8	33	6
$\mathbf{f_y}$	410	32	500	32
S	200	40	125	25
L	30Φ	6Φ	40Φ	6Φ

Thus, for each building category 15 old (no seismic design) and 15 new (modern seismic design) simulation models were analyzed to determine the vulnerability curves of old and new, low and high-rise buildings.

A total of 60 simulation models were created. Each model was analyzed using the 7 acceleration time-history records created from the response spectrums of the Microzonation study (CGSD, 2000), as mentioned earlier. A total of 420 time-history analysis were undertaken on the 4 (2 old and 2 new for each category) X 15 simulation models. The chosen 3 damage levels included in EC8-Part 3 (CEN, 1998) are attained when a column reaches,

(1) Damage Limitation (DL): Its yield rotational capacity.
(2) Significant Damage (SD): ¾ of its ultimate rotational capacity.
(3) Near Collapse (NC): Its ultimate rotational capacity and its shear capacity as defined in the code.

The top storey displacement at each damage level is recorded and transformed to spectral displacement (Sd) using the equation 4.1.

$$Sd_{k\times m\times j} = \frac{U_{k\times m\times j}}{\Gamma_1 \phi_{N1}} \tag{4.1}$$

A fourth damage level was also considered for the collapse of the building which was assumed to take place if all columns of a floor reach damage level 3 or a maximum inter-storey drift of 4% is reached.

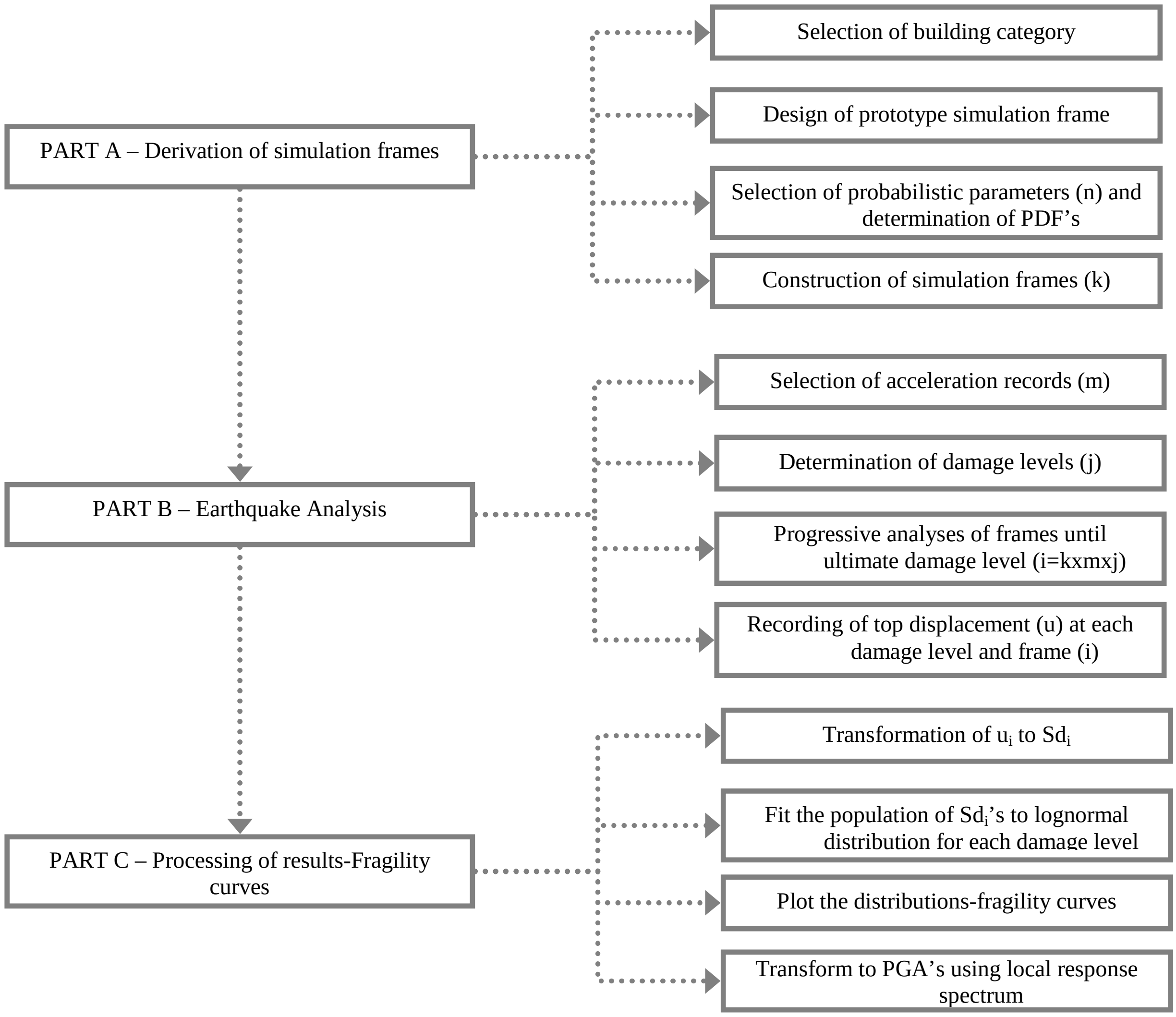

Figure 4.1. Framework for the derivation of analytical fragility curves

Each acceleration record was progressively increased in magnitude until the attainment of the ultimate damage level by a column. The mean values of spectral displacement and the corresponding standard deviation for all simulation models were recoded from the analysis results. An example for old models is shown in Table 4.3. By fitting these statistical values to a lognormal distribution the Sd fragility curves were created for each simulation model and damage level.

Table 4.3. Mean and standard deviation values of the Sd fragility curves for the 4 damage levels.

Sd (m)	DL		SD		NC		FAIL	
	μ	σ	μ	Σ	μ	σ	μ	Σ
LRO	0.055	0.27	0.07	0.30	0.09	0.28	0.11	0.28
HRO	0.13	0.28	0.15	0.29	0.19	0.35	0.25	0.31

The response spectrum for Limassol included in the Microzonation study (CGSD, 2000) was used to transform the spectral displacement values to peak ground accelerations (PGA). This transformation was deemed necessary in order to establish a link between the fragility curves and the three hazard scenarios in Table 3.1. These hazard scenarios will be used later for risk assessment and mitigation. Similarly to the Sd curves, fragility curves for each simulation model and damage level were created by fitting the mean and standard deviation values of PGA to lognormal distribution. The statistical data of the PGA fragility curves for old buildings are shown in Table 4.4.

Table 4.4. Mean and standard deviation values of the PGA fragility curves for the 4 damage levels

PGA (g)	**DL**		**SD**		**NC**		**FAIL**	
	μ	**σ**	**μ**	**Σ**	**μ**	**σ**	**μ**	**Σ**
LRO	0.13	0.28	0.2	0.39	0.27	0.38	0.33	0.41
HRO	0.17	0.24	0.21	0.37	0.3	0.5	0.44	0.39

A set of the derived fragility curves for LRO buildings are shown in Figure 4.2.

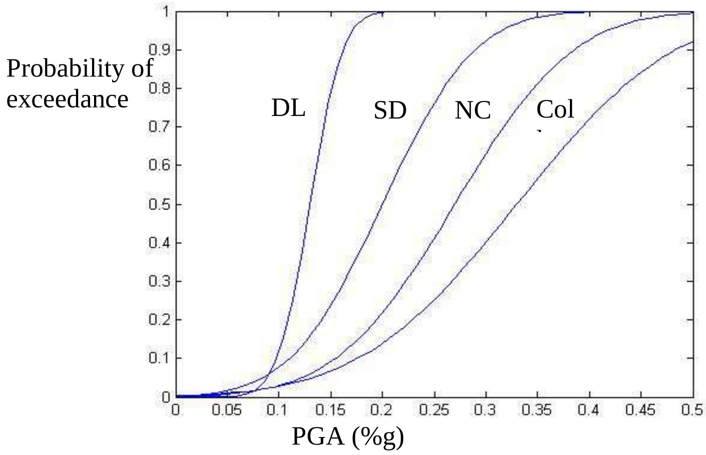

Figure 4.2. Derived fragility curves for LRO buildings

For verification purposes, some of the derived mean PGA fragility curves were compared to similar ones derived using a different approach in HAZUS (NIBS, 1999). It was observed that similarities exist in both the building categories and some of the damage levels used in our study. In particular, damage level 1 (DL) was found to be very similar in description to moderate damage level in HAZUS (NIBS, 1999) since in both cases yielding of the reinforcement takes place. In addition, damage level 3 (NC) was found similar in description to extensive damage level in HAZUS (NIBS, 1999) since in both cases members reach their ultimate capacity. The comparison of the corresponding mean PGA's for the 2 abovementioned damage levels for all building categories is shown in Table 4.5.

Table 4.5. Comparison of the derived mean PGA limits with corresponding ones in HAZUS

Building Category	Damage Level	PGA	PGA (HAZUS)
LRN	DL/Moderate	0.25g	0.35g
	NC/Collapse	1g	0.7g
HRN	DL/Moderate	0.25g	0.22g
	NC/Collapse	0.5g	0.6g
LRO	DL/Moderate	0.13g	0.15g
	NC/Collapse	0.27g	0.27g
HRO	DL/Moderate	0.17g	0.15g
	NC/Collapse	0.3g	0.27g

The comparison shows good agreement between the derived mean PGA values in this study with the corresponding ones in HAZUS (NIBS, 1999) for similar damage levels. This observation increases the level of confidence of the fragility curves produced in this study and the assumptions made.

5. EARTHQUAKE VULNERABILITY CURVES

In order to perform risk calculations, the above derived fragility curves need to be transformed into vulnerability curves by assigning damage ratio (DR) values for each damage level. This damage ratio corresponds to the ratio of the repair cost to the replacement cost. Through this transformation it will be possible to calculate the monetary losses associated to different hazard scenarios and thus proceed to risk calculations.

Due to lack of empirical monetary loss data for each damage level, the correlation of the damage levels to DR's had to be defined using similar work in the literature. It was found in HAZUS that for the two damage levels compared in the previous section, DR's of 10% and 50% were adopted respectively. Further to the HAZUS proposals, a complete set of DR's for a number of damage levels are proposed by Kappos (2006) in a similar work for vulnerability assessment. Kappos (2006) is using 6 damage levels the first two though are for post yielding of the reinforcement and thus are not considered herein. For the two damage levels discussed above, Kappos (2006) proposes a DR=5% and DR=45%, respectively, which are in good correlation to the HAZUS proposals. Further to that, a comparison of the description of Kappos (2006) damage levels to the ones used herein showed good correlation and thus it was decided to adopt Kappos (2006) damage ratio values. The adopted mean damage ratios for each damage level are shown in Table 5.1.

Table 5.1. Mean damage ratios used for each damage level

Damage Level	Damage Ratio (%)
Damage Limitation	5
Significant Damage	20
Near Collapse	45
Collapse	80

For each building category, the vulnerability curve corresponds to the fragility curve at a damage ratio of 50%. Therefore the mean PGA of the vulnerability curve for each building category is found by adding the products of the mean values of PGA of each fragility curve (damage level) with the corresponding damage ratio. By fitting this value into a lognormal distribution the vulnerability curve of each building category is constructed. This procedure is applied to the results of both old and new simulation models and the corresponding vulnerability curves for low-rise buildings are shown in Figure 5.1.

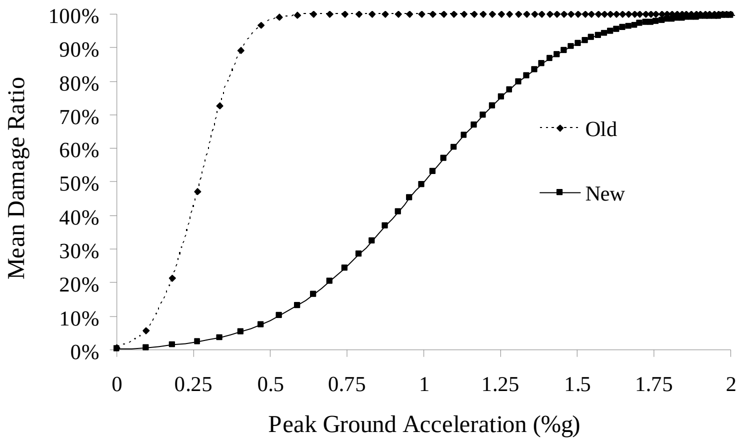

Figure 5.1. Mean damage ratio vulnerability curves for low-rise buildings.

For each building category, the curve for old buildings is used to quantify the expected damage if the buildings remain as they are with no strengthening, whereas the second curve shows the expected mean damage if full strengthening (100% strengthening) is applied to bring the building to modern earthquake resistance standards. Intermediate levels of strengthening can be evaluated using linear interpolation between the two extremes. In this way the expected damage for the 3 preselected seismic hazard scenarios can be found depending on the level of strengthening which will be applied on the building.

6. EARTHQUAKE RISK CALCULATIONS-CONCLUSIONS

The final part of the paper discusses the issues involved in the calculation of the earthquake risk. As it was shown before, it is possible to evaluate in monetary terms the expected damage from preselected seismic hazard scenarios depending on the assumed level of strengthening. Since seismic scenarios are correlated to the required remaining life of the building, the expected damage (risk) is influenced by the adopted remaining life and level of strengthening.

At this point all the tools required to evaluate the extent of damage from future events based on the decisions for pre-event strengthening were developed. The next and final step is to evaluate the cost of strengthening and, by comparing it to the damage cost, decide which level of strengthening will result in the most beneficious loss. Loss is defined as the cost of strengthening invested pre-earthquake to increase the safety of the buildings plus the cost of repair of any post earthquake damage. The cost for a 100% strengthening of an existing building in these two categories was assumed to be 20% of the replacement value based on data obtained from local practice. Based on this assumption the cost of strengthening was calculated for each level of strengthening and compared to the damage cost obtained from the vulnerability curves. The procedure was applied for both categories and repeated for the 3 hazard scenarios and a number of strengthening levels.

It was found that results differ between low and high rise buildings mainly due to the fact that a larger remaining period was assumed for the high-rise. Since their replacement is a very difficult process due to a variety of reasons, such as multiple ownership, it was decided to adopt a remaining period of 50 years for their strengthening. It was shown that for this seismic hazard scenario the possible losses drop significantly if a substantial strengthening is applied. In particular it was shown that investing for approximately 70% strengthening (very close to the new Eurocode 8 standards) will reduce the risk in half. Such strengthening may be achieved by applying shear walls at the ground floor and thus remove the soft storey failure potential. Since a 100% strengthening is not proposed, the strengthening of beams and slabs especially at the higher floors may be left for post-earthquake repair.

In the case of low-rise buildings a return period of 20 years was decided since most of them date back to the 80's (already 30-40 years old) and their replacement is a much easier process. Again it was attempted to half the risk using pre-earthquake strengthening and for that it was found that a 40% strengthening (spending 8% of the replacement cost of the building) satisfies this criterion. It is proposed that this investment includes jacketing of the columns or the replacement of an existing masonry with a shear wall, which is even less costly. Further strengthening of beams or slabs is not proposed given that there is no obvious loss of strength or serviceability.

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