Seismic Fragility Functions for Masonry Buildings in Romania

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SUMMARY:
In this paper the calibration of intensity based seismic fragility functions for unreinforced masonry buildings is based on data collected in Iasi city during the post-earthquake survey after March 4 1977 Vrancea subcrustal earthquake (M_w=7.4). The damage grades / states used in the survey are: 1-Negligible, 2-Slight, 3-Moderate, 4-Heavy, 5-Collapse. The results of the survey considered in the paper are for three building typologies:

B1 – old non-engineered unreinforced masonry buildings with flexible floors;
B2 – unreinforced masonry buildings with cast-in-place RC floors;
B3 – unreinforced masonry buildings with precast RC floors.

The damage of a given building typology is expressed as the mean and variance of the damage grade conditional upon a given MSK macro-seismic intensity.
An analytical model is selected to infer the damage grades corresponding to seismic intensities other than the ones directly obtained from post-earthquake survey. The distribution of damage grade is calculated using Beta distribution of probability. The damage probability matrices and seismic fragility functions for unreinforced masonry buildings are obtained.

Keywords: Seismic, fragility, vulnerability, masonry, Romania

1. INTRODUCTION

The fragility and vulnerability functions, along with the seismic hazard curves, are the main ingredients in developing a seismic risk assessment. A comprehensive review of methods used for assessing seismic fragility and vulnerability is given in (Calvi et. al, 2006).

In order to estimate the fragility functions several methods can be used: empirical, expert-opinion based, analytical and hybrid. The empirical method for developing fragility functions for masonry buildings was used in Europe by several researchers (Nuti et. al, 1998, Lagomarsino and Giovinazzi, 2006, Colombi et. al, 2008, Rota et. al, 2008). Nevertheless, the empirical fragility functions have the shortcoming of being tributary to the macroseismic intensities encountered in the surveyed region and to the specificities of the design and construction techniques within the region from where the seismic damage data is observed and collected.

In the past ten years at least two European Projects, RISK-UE (Mouroux et. al, 2004, Vacareanu et.al, 2005) and SYNER-G (ttp://www.vce.at/SYNER-G/), considered and discussed in deep the issue of seismic fragility functions for masonry buildings. In United States expert-opinion based fragility functions for masonry buildings are given in HAZUS-MH-MR4 Earthquake Technical Manual and ATC 13.

The methods for obtaining fragility functions model the seismic damage using a discrete damage states scale. The number of damage states used depends on the scale used: ATC 13 uses 6 damage states, EMS 98 (Grünthal, 1998) uses 5 damage states and HAZUS-MH-MR4 uses 4 damage states. In this paper a 5 damage states scale is used. The fragility functions are expressed as probability distributions conditional upon the level of the ground shaking described by an intensity measure. Several intensity measures are used by various researches: macroseismic intensity (MSK-64, MCS, EMS-98), ground motion parameters (PGA), structural response parameters (spectral displacement for a given period of vibration). Concerning the probability distributions, several types might be considered appropriate: lognormal, binomial, Beta. In this paper the intensity measure is expressed in terms of MSK-64 macroseismic intensity and the distribution of probability is Beta.

The basic Romanian data on unreinforced masonry building damage during strong earthquakes in Romania comes from *The Romanian Earthquake on March 4, 1977 – Balan St, et.al. – coordinators, 1982* and from the Annex IV of the Report to the 8th ECEE, 1986, entitled *Some data on vulnerability obtained in European countries*, by Working Group *Vulnerability and Risk Analysis for individual structures and systems* of *EAEE*. The damage survey was performed in Iasi city on a sample of several thousands unreinforced masonry and reinforced concrete buildings after Vrancea earthquake of March 4, 1977 (moment magnitude M_w=7.4). The survey was performed on the basis of individual forms filled in on the site. Residential buildings, schools and hotels were included in the sample. The results of the survey carried out in Iasi were expressed in terms of building damage grade, *DG* and corresponding site intensity. The *DG* was quantified according to the *MSK* intensity scale. Results for Iasi, relevant for this research, are given for three typologies of buildings:

B1 – old non-engineered unreinforced masonry buildings with flexible floors;
B2 – unreinforced masonry buildings with cast-in-place RC floors built after 1950;
B3 – unreinforced masonry buildings with precast RC floors built after 1950.

A representative non-engineered unreinforced masonry building seismically damaged by the March 4, 1977 Vrancea earthquake is presented in Figure 3.1.a.

2. DAMAGE DATA FROM POST-EARTHQUAKE INSPECTION

The classification of masonry building damage, as well as the damage grades / states considered in the survey are presented in Table 2.1.

Table 2.1. Classification of masonry buildings’ damage (ECEE, 1986)

Damage grade Damage state	Damage description
Grade 1: Negligible	No structural damage Slight non-structural damage Hair-line cracks in very few walls Fall of small pieces of plaster only Fall of loose stones from upper parts of buildings in very few cases
Grade 2: Slight	Slight structural damage Moderate non-structural damage Cracks in many walls Fall of fairly large pieces of plaster Partial collapse of chimneys
Grade 3: Moderate	Moderate structural damage Heavy non-structural damage Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
Grade 4: Heavy	Heavy structural damage Very heavy non-structural damage Serious failure of walls; partial structural failure of roofs and floors.
Grade 5: Collapse	Very heavy structural damage Total or near total collapse.

The damage data on masonry buildings in Iasi incurred by March 4, 1977 Vrancea earthquake are presented in Table 2.2. The building damage is expressed as the mean and standard deviation of the damage grade, *DG* considered for a given seismic intensity and for a given building typology.

Table 2.2. Masonry buildings' damage data collected in Iasi city after 1977 Vrancea earthquake (ECEE, 1986)

Building typology	B1			B2			B3		
MSK Intensity	# of bldgs.	Mean *DG*	Stdev *DG*	# of bldgs.	Mean *DG*	Stdev *DG*	# of bldgs.	Mean *DG*	Stdev *DG*
$VI^{1/2}$	751	1.40	1.04	18	0.44	0.68	36	1.73	1.25
$VII^{1/2}$	910	2.75	1.26	17	0.88	0.83	77	2.18	1.22

3. PROCESSING OF DAMAGE DATA FROM POST-EARTHQUAKE INSPECTION

The normalized damage grade, d – with values in-between 0 and 1.0 – is defined as the ratio of the effective damage grade, *DG* to the maximum damage grade equal to 5.0, i.e.

$$d=DG/5 \tag{3.1}$$

Consequently, the mean normalised damage grade is:

$$Mean\ d = Mean\ DG/5 \tag{3.2}$$

and the standard deviation of the normalised damage grade is:

$$St.dev\ d = St.dev\ DG/5 \tag{3.3}$$

The damage data from Table 2.2 converted into normalised damage data according to relations (3.2) and (3.3) are represented in Figure 3.1b.

For the vulnerability analysis of masonry structures, the following model adapted from (Cherubini et. al, 1999) is selected:

$$d = 0.5 + 0.25\{\arctan[0.55(I - 10.2 + 0.05 I_v)]\} \qquad 0 \le d \le 1 \tag{3.4}$$

where:
I_v – vulnerability index
I – seismic intensity.

Based on the damage data given in Table 2.2, the vulnerability index of relation (3.4) is obtained through linear regression analysis. The values of the vulnerability index are reported in Table 3.1. The damage data, as well as the relation (3.4) fitted to the unreinforced masonry buildings' survey damage data collected in Iasi (i.e. Table 2.2 data divided by 5.0), are represented in Figure 3.2 -3.5.

Table 3.1. Vulnerability index, I_v

Building type in survey	*B1*	*B2*	*B3*
Vulnerability index, I_v	38	34	30

Taking into account the I_v values form Table 3.1 and relation (3.4), the following correspondence given in Table 3.2 between building typology, vulnerability index and average normalised damage grade is obtained.

Table 3.2. Correspondence between building typology and average normalised damage grade

Masonry building typology	Vulnerability index, I_v	Mean normalised damage grade d for seismic intensity:			
		VI	VII	VIII	IX
B1	55	0.26	0.20	0.24	0.31
B2	30	0.39	0.24	0.35	0.51
B3	50	0.63	0.35	0.57	0.70

Figure 3.1.a. Faculty of Medicine, Bucharest. Seismic damage on March 4 1977 (Lungu et.al. 2000)

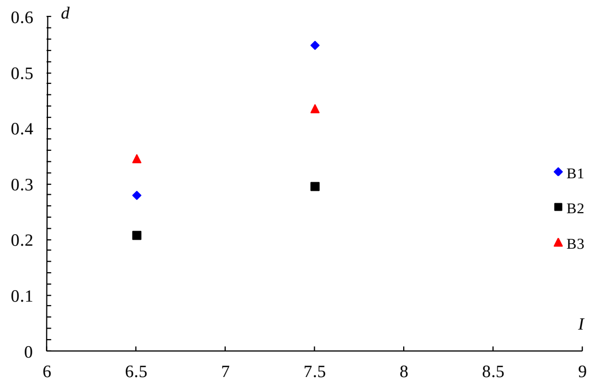

Figure 3.1.b. Average normalized damage grade versus macroseismic intensity

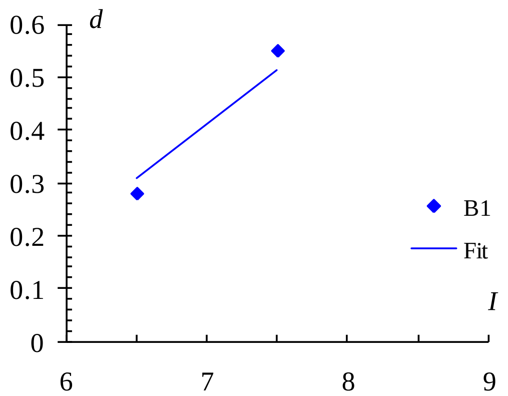

Figure 3.2. Observed and fitted data - B1 building typology

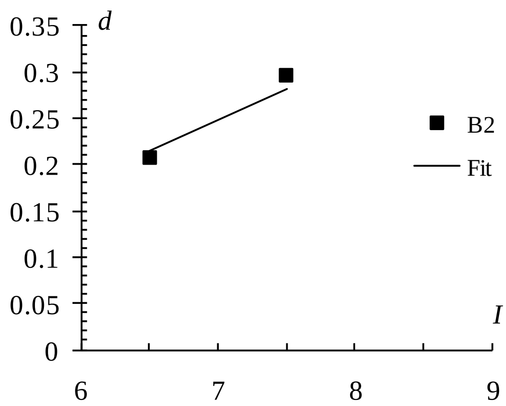

Figure 3.3. Observed and fitted data - B2 building typology

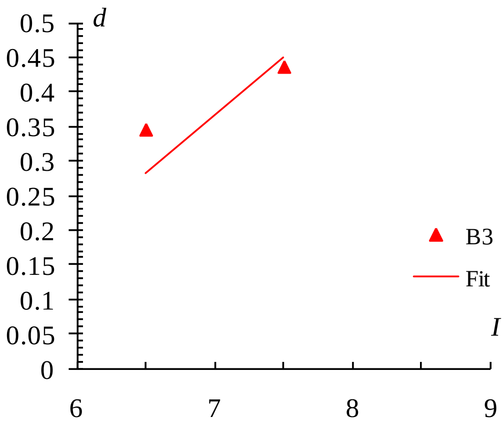

Figure 3.4. Observed and fitted data – B3 building typology

4. INTENSITY BASED FRAGILITY FUNCTIONS FOR MASONRY BUILDINGS

The distribution of damage grade is calculated using Beta distribution of probability and it is defined by the following probability density function (Evans et.al, 2000):

$$f_X(x) = \begin{cases} \dfrac{1}{B(q,r)} \cdot \dfrac{(x-a)^{q-1} \cdot (b-x)^{r-1}}{(b-a)^{q+r-1}}, & a \le x \le b \\ \to 0, & otherwise \end{cases} \qquad (4.1)$$

where a=0, b=6, and $B(q,r)$ is the Beta function:

$$B(q,r) = \frac{\Gamma(q) \cdot \Gamma(r)}{\Gamma(q+r)} \qquad (4.2).$$

The parameters q and r of the distribution are related to the mean and the variance of the random damage grade, DG as follows:

$$Mean\ DG = a + \frac{q}{q+r}(b-a) \qquad (4.3)$$

$$(St.dev\,DG)^2 = \frac{q \cdot r}{(q+r)^2 (q+r+1)}(b-a)^2 \qquad (4.4).$$

The values of q, r and $B(q,r)$ obtained from relations (4.3) and (4.4) solved recursively for the values of mean and variance of the damage grade from Tables 2.2 and 3.2 are given in Tables 4.1 - 4.3.

Table 4.1. Values of q and r parameters for B1 masonry buildings typology

Intensity	*q*	*r*	*B(q,r)*
$VI^{1/2}$	1.00	3.30	0.26
VII	1.24	2.52	0.27
$VII^{1/2}$	1.33	1.58	0.43
VIII	1.53	1.40	0.42
$VIII^{1/2}$	4.21	1.79	0.06
IX	4.50	1.50	0.09

Table 4.2. Values of q and r parameters for B2 masonry buildings typology

Intensity	*q*	*r*	*B(q,r)*
$VI^{1/2}$	1.06	5.04	0.17
VII	1.46	5.84	0.06
$VII^{1/2}$	1.41	4.29	0.11
VIII	1.74	4.26	0.06
$VIII^{1/2}$	2.70	3.30	0.03
IX	3.44	2.56	0.04

Table 4.3. Values of q and r parameters for B3 masonry buildings typology

Intensity	*q*	*r*	*B(q,r)*
$VI^{1/2}$	1.69	4.31	0.07
VII	2.08	3.92	0.05
$VII^{1/2}$	1.05	1.85	0.50
VIII	1.53	1.67	0.33
$VIII^{1/2}$	4.01	1.99	0.05
IX	4.37	1.63	0.07

The cumulative distribution function of the damage grade, DG is obtained with the relation:

$$F_X(x)=\int_a^x f_X(u)du \quad (4.5)$$

The discrete Beta density probability function is calculated from the probabilities associated with damage grades k and k+1 (k = 0, 1, 2, 3, 4, 5), as follows:

$$P(k)=F_X(k+1)-F_X(k) \quad (4.6).$$

Examples of distributions of damage grade, *DG* for B1, B2 and B3 building typologies and macroseismic intensity IX are presented in Figures 4.1…4.3. The probability density functions and the cumulative distribution functions are obtained with relations (4.1) and (4.5) with q and r values from Tables 4.1 - 4.3.

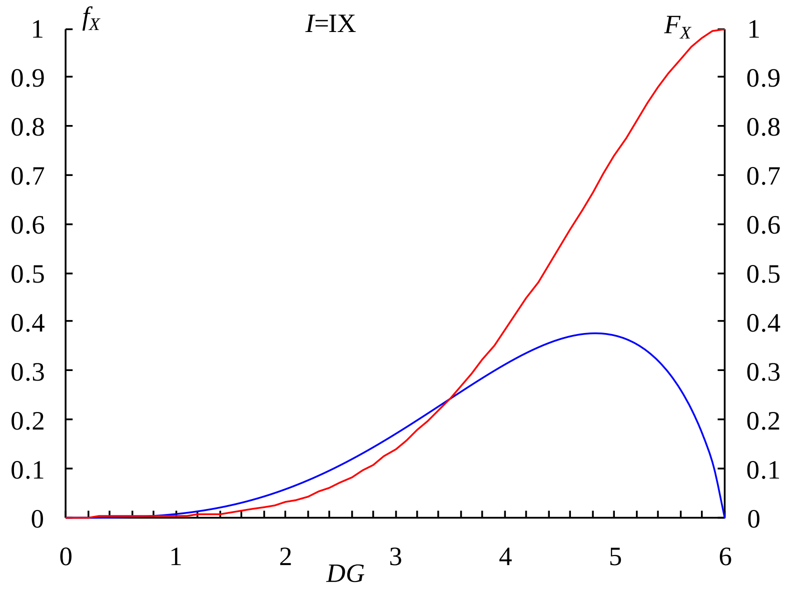

Figure 4.1. B1 building typology - probability functions of damage grades for seismic intensity IX

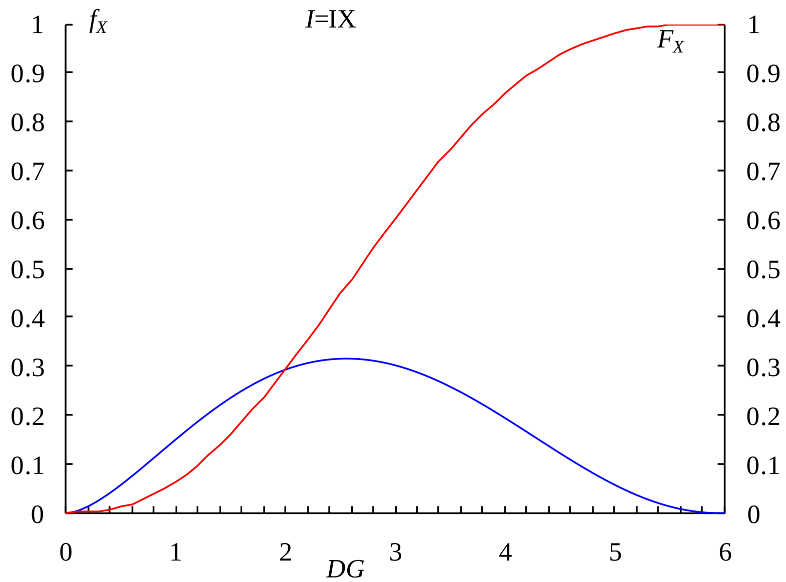

Figure 4.2. B2 building typology - probability functions of damage grades for seismic intensity IX

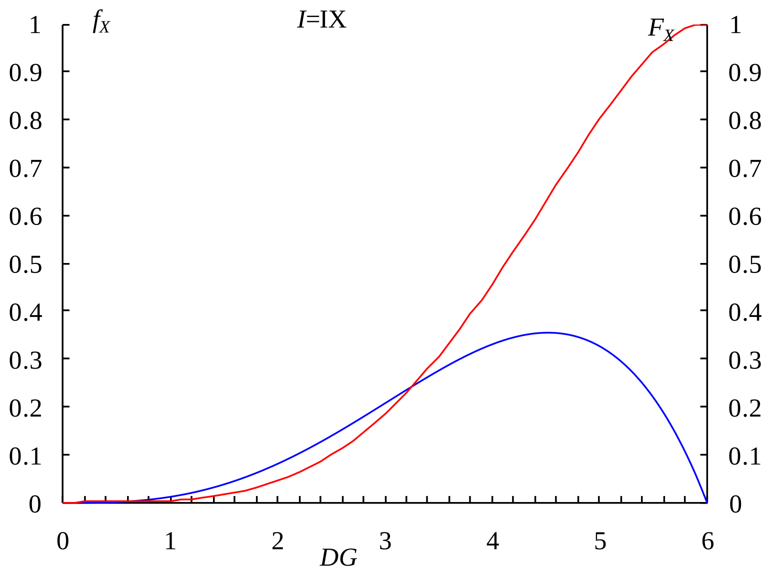

Figure 4.3. B3 building typology - probability functions of damage grades for seismic intensity IX

The damage probability matrices (DPM) express in a discrete form the conditional probability of obtaining a damage grade j, due to a seismic intensity i, P[$DG = j \mid I = i$]. Based on the relation (4.6), the damage probability matrices, DPM are obtained for B1, B2 and B3 building typologies, as given in Tables 4.4 – 4.6.

Table 4.4. Damage probability matrix for B1 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		VI$^{1/2}$	VII	VII$^{1/2}$	VIII	VIII$^{1/2}$	IX
0	Undamaged	4.35E-01	2.73E-01	1.48E-01	9.62E-02	1.84E-03	7.79E-04
1	Negligible	2.94E-01	2.82E-01	2.05E-01	1.69E-01	2.78E-02	1.52E-02
2	Slight	1.66E-01	2.18E-01	2.11E-01	2.01E-01	1.10E-01	7.28E-02
3	Moderate	7.75E-02	1.42E-01	1.95E-01	2.10E-01	2.42E-01	1.94E-01
4	Heavy	2.48E-02	6.97E-02	1.57E-01	1.94E-01	3.57E-01	3.53E-01
5	Collapse	2.83E-03	1.53E-02	8.38E-02	1.29E-01	2.61E-01	3.64E-01

Table 4.5. Damage probability matrix for B2 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		VI$^{1/2}$	VII	VII$^{1/2}$	VIII	VIII$^{1/2}$	IX
0	Undamaged	5.63E-01	4.80E-01	3.79E-01	2.78E-01	6.29E-02	1.39E-02
1	Negligible	2.92E-01	3.48E-01	3.43E-01	3.58E-01	2.30E-01	1.03E-01
2	Slight	1.11E-01	1.35E-01	1.88E-01	2.35E-01	3.09E-01	2.34E-01
3	Moderate	3.01E-02	3.29E-02	7.28E-02	1.03E-01	2.55E-01	3.11E-01
4	Heavy	4.41E-03	3.76E-03	1.63E-02	2.52E-02	1.24E-01	2.57E-01
5	Collapse	1.41E-04	7.41E-05	9.48E-04	1.60E-03	1.91E-02	8.09E-02

Table 4.6. Damage probability matrix for B3 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		VI$^{1/2}$	VII	VII$^{1/2}$	VIII	VIII$^{1/2}$	IX
0	Undamaged	2.95E-01	1.74E-01	2.56E-01	1.18E-01	3.27E-03	1.15E-03
1	Negligible	3.59E-01	3.34E-01	2.44E-01	1.98E-01	4.11E-02	2.00E-02
2	Slight	2.26E-01	2.83E-01	2.03E-01	2.20E-01	1.40E-01	8.80E-02
3	Moderate	9.58E-02	1.56E-01	1.55E-01	2.10E-01	2.72E-01	2.16E-01
4	Heavy	2.27E-02	4.88E-02	1.02E-01	1.69E-01	3.44E-01	3.58E-01
5	Collapse	1.37E-03	4.23E-03	3.96E-02	8.49E-02	1.99E-01	3.17E-01

The fragility function defining the probability of reaching or exceeding a certain damage grade, *DG* is obtained directly from the Beta cumulative distribution function:

$$P[DG \geq k] = 1 - F_X(k) \quad (4.7).$$

The discrete values of the fragility functions are given in Tables 4.7 – 4.9.

Table 4.7. Discrete values of fragility functions for B1 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		$VI^{1/2}$	VII	$VII^{1/2}$	VIII	$VIII^{1/2}$	IX
1	Negligible	5.65E-01	7.27E-01	8.52E-01	9.04E-01	9.98E-01	9.99E-01
2	Slight	2.71E-01	4.45E-01	6.47E-01	7.34E-01	9.70E-01	9.84E-01
3	Moderate	1.05E-01	2.27E-01	4.36E-01	5.33E-01	8.61E-01	9.11E-01
4	Heavy	2.77E-02	8.50E-02	2.41E-01	3.23E-01	6.18E-01	7.18E-01
5	Collapse	2.83E-03	1.53E-02	8.38E-02	1.29E-01	2.61E-01	3.64E-01

Table 4.8. Discrete values of fragility functions for B2 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		$VI^{1/2}$	VII	$VII^{1/2}$	VIII	$VIII^{1/2}$	IX
1	Negligible	4.37E-01	5.20E-01	6.21E-01	7.22E-01	9.37E-01	9.86E-01
2	Slight	1.45E-01	1.72E-01	2.78E-01	3.64E-01	7.07E-01	8.83E-01
3	Moderate	3.47E-02	3.67E-02	9.00E-02	1.30E-01	3.98E-01	6.49E-01
4	Heavy	4.56E-03	3.83E-03	1.72E-02	2.68E-02	1.43E-01	3.38E-01
5	Collapse	1.41E-04	7.41E-05	9.48E-04	1.60E-03	1.91E-02	8.09E-02

Table 4.9. Discrete values of fragility functions for B3 building typology

Damage grade, *DG*	Damage state	Seismic intensity					
		$VI^{1/2}$	VII	$VII^{1/2}$	VIII	$VIII^{1/2}$	IX
1	Negligible	7.05E-01	8.26E-01	7.44E-01	8.82E-01	9.97E-01	9.99E-01
2	Slight	3.46E-01	4.92E-01	5.00E-01	6.83E-01	9.56E-01	9.79E-01
3	Moderate	1.20E-01	2.09E-01	2.97E-01	4.64E-01	8.15E-01	8.91E-01
4	Heavy	2.41E-02	5.30E-02	1.42E-01	2.54E-01	5.43E-01	6.75E-01
5	Collapse	1.37E-03	4.23E-03	3.96E-02	8.49E-02	1.99E-01	3.17E-01

The expected damage grades for each seismic intensity and for each building typology given in Table 4.10 are obtained using the values of the damage states probabilities given in Tables 4.4 – 4.6. The expected damage grades are evaluated as weighted average of discrete damage grades, the weights being the damage grade/state probabilities.

Table 4.10. Expected damage grades for B1, B2 and B3 building typologies

Building typology	Seismic intensity					
	$VI^{1/2}$	VII	$VII^{1/2}$	VIII	$VIII^{1/2}$	IX
B1	0.97	1.50	2.26	2.62	3.71	3.97
B2	0.62	0.73	1.01	1.25	2.20	2.94
B3	1.20	1.58	1.72	2.37	3.51	3.86

The expected damage states for each seismic intensity and for each building typology given in Table 4.11 are obtained based on the following algorithm:

- if expected damage grade lies in the interval [0, 0.5], then the expected state is undamaged;
- if expected damage grade lies in the interval (0.5, 1.5], then the expected state is negligible damage;
- if expected damage grade lies in the interval (1.5, 2.5], then the expected state is slight damage;

- if expected damage grade lies in the interval (2.5, 3.5], then the expected state is moderate damage;
- if expected damage grade lies in the interval (3.5, 4.5], then the expected state is heavy damage;
- if expected damage grade lies in the interval (4.5, 5], then the expected state is collapse.

Table 4.11. Expected damage states for B1, B2 and B3 building typologies

Building typology	Seismic intensity					
	$VI^{1/2}$	VII	$VII^{1/2}$	VIII	$VIII^{1/2}$	IX
B1	Negligible	Negligible	Slight	Moderate	Heavy	Heavy
B2	Negligible	Negligible	Negligible	Negligible	Moderate	Moderate
B3	Negligible	Slight	Slight	Slight	Heavy	Heavy

5. CONCLUSIONS

Based on some of the most important contributions in the field of fragility assessment of unreinforced masonry buildings in Europe, a brief review of the development of fragility functions in the past decades is presented in this paper.

The results on seismic behaviour of unreinforced masonry buildings in Romania are scarce and are based on the seismic damaged incurred to masonry buildings in Iasi and Bucharest during March 4 1977 Vrancea subcrustal earthquake. The data sample is limited and thus the results are subjected to sampling uncertainties.

In this paper, the fragility functions are obtained through empirical methods and are calibrated based on statistics of observed damage of unreinforced masonry buildings from past earthquakes in Iasi, Romania. Previous research on seismic fragility of Romanian unreinforced masonry buildings (EAEE, 1986) discussed the issue of damage probability matrices based on the binomial distribution of probability of damage grade. In this paper Beta distribution of probability of damage grade is employed instead and the results are given in the form of damage probability matrices as well as in the form of fragility functions. The expected damage grades of masonry buildings derived analytically in section 4 of the paper correspond to the observed ones in Iasi after March 4 1977 Vrancea subcrustal earthquake for macroseismic intensities $VI^{1/2}$ and $VII^{1/2}$.

One can notice the better seismic performance of unreinforced masonry buildings with rigid floors with respect to the unreinforced masonry buildings with flexible floors and the better seismic performance of buildings with cast-in-place RC floors versus buildings with precast floors. The later conclusion is because of the poor seismic behaviour of connections between the precast slabs and the unreinforced masonry walls.

Though the results obtained in the paper are based on the seismic damage data collected in Iasi, the results are relevant for unreinforced masonry buildings all around Romania since the layout, techniques and details of the unreinforced masonry bearing walls and of the slabs were almost uniform in Romania before 1977.

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