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STATISTICAL ASSESSMENT OF THE VULNERABILITY OF UNREINFORCED MASONRY BUILDINGS

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SUMMARY

A methodology followed for the development of 1st level fragility curves for Greek URM buildings is presented. The data used are statistical data from Greek earthquakes, the Thessaloniki 1978 and the Aegion 1995 events, with some additional data from the Pyrgos 1993 earthquake used for comparison purposes. The databases of the first two earthquakes are briefly presented and processed using a filtering technique, first applied within the framework of this study. Furthermore, the resulting damage matrices are compared with the available Italian ones. The resulting vulnerability curves correlate the EMS98 intensity to the probability that a building type exceeds a particular damage state and are correlated to other proposed curves.

1. INTRODUCTION

The adopted methodology for the 1st level vulnerability analysis of unreinforced masonry (URM) buildings is based on the statistical evaluation and processing of empirical data collected from past Greek earthquakes, more specifically the Thessaloniki 1978 event and the Aegion 1995 events, backed up by some additional data from the Pyrgos 1995 earthquake.

The objectives of this contribution are the presentation of the methodology for the development of the vulnerability curves as well as the comparison with other available curves that have been proposed in the past.

2. OUTLINE OF THE METHODOLOGY

2.1 General

The so-called 1st level methodology aims at the calculation of practical closed-form equations, which correlate an excitation characteristic (i.e. PGA or intensity) to a descriptor of the building's damage state (damage level, repair cost, etc).

2.2 Damage states

For the 1st level approach six different damage levels (states) are proposed, defined according to the damage index shown in table 1.

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The (economic) damage index is the ratio of cost of repair to cost of replacement of a building and it is deemed suitable for vulnerability assessment purposes since it is a “monetary” index.

Table 1: Definition of damage states (levels)

Damage level	Definition	Range of damage index
0	No damage	0
1	Slight damage	0-5
2	Moderate damage	5-20
3	Extensive damage	20-50
4	Very heavy damage	50-95
5	Collapse	95-100

2.3 Vulnerability Curves

It is well documented in the literature that such curves can be described by (cumulative) normal, lognormal, beta or other distribution, provided that sufficient data is available. The most common problem however when applying a purely empirical approach is the unavailability of data for several intensities. By definition, intensities up to 5 lead to negligible damage, particularly cost-wise, therefore gathering of damage data is simply not feasible, while on the other hand events with intensities greater than 8 are rare for most countries, so there are no data available. This unavailability leads to a relative abundance of statistical data in the intensity range from 6 to 8 and a lack of data in the other intensities. This makes the selection of an appropriate cumulative distribution very unreliable since the curve fit error is significant and the curve shape is not as it would be expected.

In order to overcome these problems a convenient mathematical expression, rather than a proper statistical equation has been adopted in order to fit the desired curve shape to the available data. Nonetheless, the desired curve shape resembles that of a statistical distribution, i.e. a sigma-like cumulative distribution curve.

3. BUILDING TYPES

The building types statistically analysed are single-storey and two-storey stone and brick masonry buildings. It is clear that there is no sufficient statistical information to further subdivide these classes according to type of stone, type of brick, or type of floors (rigid or flexible diaphragm). Some limited additional data concerning three-storey buildings are given in Penelis et al. (2002).

4. EVALUATION OF AVAILABLE DATABASES

As has been mentioned in the introduction, the available databases are those of the Thessaloniki 1978 earthquake (Penelis et al. 1989) and the Aegion 1995 earthquake (Fardis et al. 1999), as well as some shorter reports for the 1993 Pyrgos earthquake (Karantoni & Bouckovalas, 1997, Lekkas et al. 2000).

It is noted that damage data collected in Greece after recent earthquakes (Kalamata 1986, Pyrgos 1993, Patras 1993, Aegion 1995), although valuable, are generally not in a form that economic damage statistics can be assessed for a *representative* set of buildings. What usually happens is that the collected data concerns only buildings that have been inspected for a second time (i.e. after the initial post-earthquake rapid screening) and/or wherein some post-earthquake intervention (repair, strengthening, etc.) has taken place; furthermore, the extent of the geographical area (number of municipalities), hence the total building stock to which the data refers, is often unclear.

4.1 Thessaloniki database

The database was set up within a previous large-scale project (Penelis et al. 1989). The timing of the research (early eighties) was quite appropriate in the sense that at that time all the post-earthquake repair and/or reconstruction work was completed, hence, in addition to the standard data concerning configuration and structural system, location, and age of the buildings, cost of repair or reconstruction was also recorded for all buildings where some type of post-earthquake intervention was undertaken. This permitted, for the first (and so far only) time in Greece to have a reliable set of damage data in terms of the *economic damage index* i.e. the ratio of repair cost to replacement cost, which is the basis of most US and other schemes.

This database consists of a record of the centre of the city of Thessaloniki with randomly selected buildings with a density of 1:2 (i.e. 50% of total building stock within the selected area was recorded) with all the relevant information included, such as year of construction, material, number of storeys, first level post-earthquake damage classification (green-yellow-red tag), and (importantly) cost of repair of earthquake damage. The database includes a total of 5740 buildings, 1780 of which (31%) are unreinforced masonry ones.

This information was used in order to calculate the *level of damage* to each building by using the aforementioned *damage index*, i.e. the repair cost over replacement cost, and the definitions given in Table 1. This is believed to be the preferred index and has been successfully used in the framework of the hybrid method of vulnerability assessment, originally developed for R/C structures (Kappos et al. 1998, Kappos 2001). The post-earthquake damage classification (tag colour) was also used (despite being a generally less reliable index), for reasons explained later on.

Unfortunately the database does not include any specific information regarding the type of masonry (stone or brick) therefore the assumption that all URM buildings constructed before 1940 were stone masonry and all the rest brick masonry, was adopted, based on historical evidence on types of masonry construction in Greece provided in the literature (e.g. Karantoni & Bouckovalas, 1997).

It is known to the writers that repair of damage after the Thessaloniki earthquake has been tackled in an essentially political way, aiming to support the financially weakest parts of the local society, who were the owners of most of the URM buildings. This led to a systematic overestimation/exaggeration in classifying damaged masonry buildings as “not repairable” and opting for demolition and reconstruction, rather than repair. In order to eliminate, to the largest possible extent, this overestimation of damage, the correlation of the damage index to the first level damage classification was used as an additional criterion and three different scenarios were investigated.

The scheme for immediate post-earthquake damage classification (tagging) of buildings in Greece, initiated after the 1978 Thessaloniki earthquake, considers three damage states, *green* for immediate occupancy (light damage), *yellow* for restricted entrance (repairable damage) and *red* for unusable (heavy damage and/or partial collapse). It is widely accepted in Greece that the teams of engineers performing this post-earthquake screening tend to be conservative and guard themselves against potential liabilities, should an aftershock occur and cause injuries and/or deaths. Having that in mind, alternative interpretations were given to the data of table 2, which are directly based on the 1978 earthquake damage cost statistics, to arrive at revised matrices that are more representative of the degree of damage (as distinguished from the intervention method chosen). According to a first interpretation (table 3), all the green-tagged buildings assigned to the fourth or fifth damage state (D=4 or 5) on the basis of the damage index given in Table 1, were transferred to the second one (D=2), while all the corresponding yellow ones were transferred to the third damage state (D=3). As can be seen in table 3, a more regular distribution is obtained from the aforementioned modifications, but an apparent anomaly still exists in that buildings with D=1 are substantially less than those with D=2. It is well known that very light damage could be undetected or ignored, and lightly damaged buildings are often not repaired, hence the economic damage ratio D=0. In view of these remarks, a second interpretation was made (table 4), wherein the percentage of damage state D=1 buildings of the 1st scenario was increased to that of the damage state D=2 with a corresponding decrease in the zero damage state (D=0). Finally, as a third interpretation (table 5) the reassignment of buildings from D=0 to D=1 carried out in the 2nd interpretation was introduced into the initial damage matrices of table 2, while levels 4 and 5 were left unchanged. Overall, it is believed that the most reasonable distribution is represented by that of table 4.

Table 2: Damage matrix from Thessaloniki 1978 data, based solely on economic damage index

D	**STONE 1-3**	**STONE 1**	**STONE 2**	**BRICK 1-3**	**BRICK 1**	**BRICK 2**
0	73.06%	76.28%	63.74%	86.35%	85.00%	88.33%
1	1.36%	0.96%	2.67%	0.49%	0.25%	0.56%
2	5.21%	4.89%	4.20%	4.93%	4.75%	5.56%
3	2.89%	2.23%	5.73%	2.96%	4.00%	1.11%
4	12.27%	12.13%	12.60%	3.95%	4.75%	2.78%
5	5.21%	3.51%	11.07%	1.32%	1.25%	1.67%
MDF	**0.695**	**0.660**	**0.786**	**0.350**	**0.408**	**0.261**

Table 3: Damage matrix from Thessaloniki 1978 data, based on economic damage index and post-earthquake tagging (1st interpretation)

D	**STONE 1-3**	**STONE 1**	**STONE 2**	**BRICK 1-3**	**BRICK 1**	**BRICK 2**
0	73.06%	76.28%	63.74%	86.35%	85.00%	88.33%
1	1.36%	0.96%	2.67%	0.49%	0.25%	0.56%
2	13.79%	12.87%	14.12%	9.21%	9.25%	10.00%
3	5.53%	4.89%	8.40%	3.62%	5.00%	1.11%
4	4.33%	3.83%	6.49%	0.16%	0.25%	0.00%
5	1.92%	1.17%	4.58%	0.16%	0.25%	0.00%
MDF	**0.629**	**0.567**	**0.821**	**0.304**	**0.348**	**0.239**

Table 4: Damage matrix from Thessaloniki 1978 data, based on economic damage index and post-earthquake tagging (2nd interpretation)

D	STONE 1-3	STONE 1	STONE 2	BRICK 1-3	BRICK 1	BRICK 2
0	60.63%	64.36%	52.29%	77.63%	76.00%	78.89%
1	13.79%	12.87%	14.12%	9.21%	9.25%	10.00%
2	13.79%	12.87%	14.12%	9.21%	9.25%	10.00%
3	5.53%	4.89%	8.40%	3.62%	5.00%	1.11%
4	4.33%	3.83%	6.49%	0.16%	0.25%	0.00%
5	1.92%	1.17%	4.58%	0.16%	0.25%	0.00%
MDF	**0.753**	**0.686**	**0.935**	**0.391**	**0.438**	**0.333**

Table 5: Damage matrix from Thessaloniki 1978 data, based on economic damage index (3rd interpretation)

D	STONE 1-3	STONE 1	STONE 2	BRICK 1-3	BRICK 1	BRICK 2
0	69.21%	72.34%	62.21%	81.91%	80.50%	83.33%
1	5.21%	4.89%	4.20%	4.93%	4.75%	5.56%
2	5.21%	4.89%	4.20%	4.93%	4.75%	5.56%
3	2.89%	2.23%	5.73%	2.96%	4.00%	1.11%
4	12.27%	12.13%	12.60%	3.95%	4.75%	2.78%
5	5.21%	3.51%	11.07%	1.32%	1.25%	1.67%
MDF	**0.734**	**0.699**	**0.802**	**0.395**	**0.453**	**0.311**

It is noted that the last row in Tables 2 to 5 gives the mean damage factor (MDF), also known as mean damage grade, calculated as the weighted average of damage level DL expressed as a numeral (values from 0 to 5). The trends indicated in these tables are as expected for stone masonry buildings, in the sense that 2-storey buildings are more vulnerable than single-storey ones. On the other hand, brick masonry building statistics do not show this trend, since two-storey buildings appear to be less vulnerable than single-storey ones; there are no clear reasons for this apparent discrepancy, particularly since details of the quality of construction are not available in the database.

4.2 Aegion database

This database, compiled by the University of Patras team (Fardis et al. 1999), includes all the buildings within the centre of Aegion, among them the vast majority of the damaged R/C and URM buildings. The sample consists of 2014 buildings, 857 of which (42.5%) are unreinforced masonry buildings. The database was set up on the basis of five damage levels (0 to 4); to convert it to the 6-level classification scheme the last level (D=4) has been divided into two (D=4 and D=5) at a proportion of 70 and 30%, respectively, in general conformity with the corresponding Thessaloniki data. Characterization of each building's damage state was performed by visual inspections carried out by the research team of the University of Patras. This approach eliminates the risk of overestimating damage that is present when using the cost of repair criterion, but on the other hand is more subjective, heavily relying on experience and judgment during the visual inspection.

The damage matrices derived on the basis of Aegion data are shown in Table 6 (1 and 2 refer to the number of storeys) for the two categories (brick and stone) that are also used in the Thessaloniki database. It is noted that the sample for brick masonry buildings is small (a total of only 69 buildings, almost evenly distributed between one and two-storey).

Table 6: Damage matrix from Aegion 1995 data.

D	**STONE 1**	**STONE 2**	**STONE 1-2**	**BRICK 1**	**BRICK 2**	**BRICK 1-2**
0	48.3%	46.4%	47.4%	92.1%	45.1%	68.6%
1	26.4%	17.8%	22.1%	2.6%	12.9%	7.8%
2	7.0%	14.2%	10.6%	5.3%	16.2%	10.8%
3	10.3%	11.1%	10.7%	0.0%	17.7%	8.9%
4	5.5%	7.6%	6.6%	0.0%	5.6%	2.8%
5	2.5%	3.0%	2.8%	0.0%	2.5%	1.3%
MDF	**1.058**	**1.249**	**1.154**	**0.132**	**1.333**	**0.733**

4.3 Utilisation of the databases

Using the information from the two independent databases presented in the previous sections, for deriving damage probability matrices (DPMs) and vulnerability (fragility) curves, it is essential to firstly define the macroseismic intensity pertinent to each case.

On the basis of information reported in the literature (Kappos et al. 1998, Lekidis et al. 1999), the Thessaloniki earthquake gave an intensity 7 in the studied area, while the Aegion earthquake resulted in an intensity of 8 (in the town of Aegion). It is noted that no systematic assignment of intensities has been reported for these (and most other Greek) earthquakes; the only relatively detailed such study was for the 1993 Pyrgos earthquake (Lekkas et al. 2000). Verification that the intensity in Aegion was indeed more severe than in Thessaloniki is provided by comparison of the mean damage factor values. It is clear that the intensity in Aegion was higher than that in Thessaloniki; the only observed discrepancy is with respect to single-storey brick masonry structures, which appear to be the outliers in the Aegion statistics.

An additional effort was made to use some information from the 1993 Pyrgos earthquake, whose EMS intensity was estimated as 8 (Lekkas et al. 2000). In Table 7 only the MDF values for each building type and event are shown. It is clear that the Pyrgos and Aegion earthquakes were of similar intensity, which was higher than that in Thessaloniki; it is also confirmed that data for the single-storey brick masonry buildings is out of trend in the case of Aegion (recall the small sample in this case).

From the foregoing considerations, it appears that the reported intensity values in the three events are reasonable, at least in a comparative sense; however the absolute values of intensities that have been assumed might need additional verification and are further discussed in the following.

Table 7: Comparison of damage for the Thessaloniki (2nd interpretation), Pyrgos and Aegion events

MDF	**STONE 1**	**STONE 2**	**BRICK 1**	**BRICK 2**
Thessal.	0.68	0.93	0.44	0.33
Pyrgos	0.80	1.05	0.92	0.80
Aegion	1.05	1.25	0.13	1.30

4.4 Comparison of Greek and Italian empirical DPMs

In order to verify the intensity to be assigned to each database, as well as to get a comparative picture of damage information for masonry buildings in Southern Europe, the Italian DPMs based on the 1980 S. Italy (Irpinia) earthquakes (Braga et al, 1982; Dolce et al, 2000) have been used for comparison, while some consideration has also been given to more recent Italian data presented by Zuccaro and Papa (2002). In Table 8a the Italian DPMs for EMS class B are compared with Greek data for stone masonry, while in Table 8b the Italian DPMs for class C are compared with Greek data for brick masonry; in Figs. 1a and 1b the same information is plotted in the form of bar charts, to further assist a more meaningful comparison.

Table 8a: Comparison of Italian(class B) and Greek (2nd interpretation) damage data for stone masonry

D	**I=6**	**I=7**	**I=8**	**THESS 78**	**AEGION**
0	36.05%	18.71%	2.89%	60.63%	47.35%
1	40.70%	37.43%	15.61%	13.79%	22.10%
2	18.60%	29.82%	31.21%	13.79%	10.60%
3	4.07%	11.70%	31.21%	5.53%	10.70%
4	0.58%	2.34%	15.61%	4.33%	6.51%
5	0.00%	0.00%	3.47%	1.92%	2.79%
MDF	**0.924**	**1.415**	**2.514**	**0.849**	**1.154**

Table 8b: Comparison of Italian(class C) and Greek (2nd interpretation) damage data for brick masonry

D	**I=6**	**I=7**	**I=8**	**THESS 78**	**AEGION**
0	71.50%	40.10%	13.09%	76.81%	68.60%
1	24.80%	40.20%	32.90%	9.50%	7.75%
2	3.51%	16.19%	33.01%	9.50%	10.75%
3	0.19%	3.21%	16.49%	3.86%	8.85%
4	0.00%	0.30%	4.10%	0.16%	2.84%
5	0.00%	0.00%	0.40%	0.16%	1.22%
MDF	**0.324**	**0.834**	**1.668**	**0.415**	**0.732**

From Tables 7a, 7b and Figs. 1a and 1b, it appears that damage in the Thessaloniki event corresponds to an intensity level between 6 and 7 (closer to 6) in the light of the Italian data, while the Aegion earthquake damage corresponds to a value closer to 7.

The observed differences between the Italian and Greek data should be attributed to a combination of the following factors

- Differences in the way that URM buildings were assigned to each class in each country, Italian buildings in Irpinia appear to be more vulnerable for the same intensity, a remark also made in the recent study by Zuccaro and Papa (2002)
- Differences in the way intensities were assigned (this assignment appears to be more 'conservative' in the Greek data); the data in fig. 1 would imply that Thessaloniki was closer to the Italian I=6 and Aegion closer to I=7, rather than 7 and 8, respectively

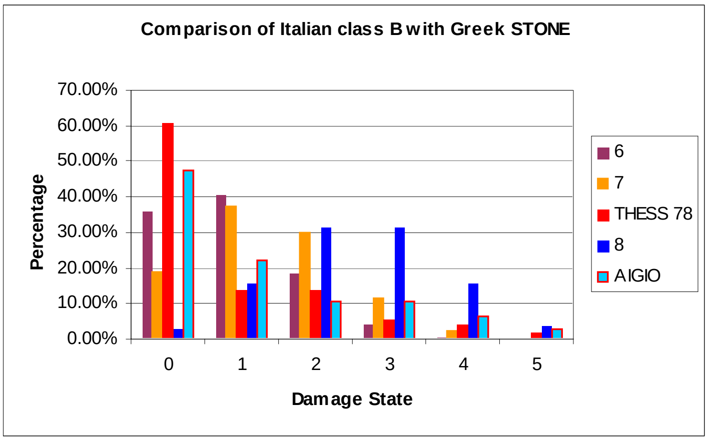

fig. 1a: Comparison of Italian and Greek damage data for stone masonry

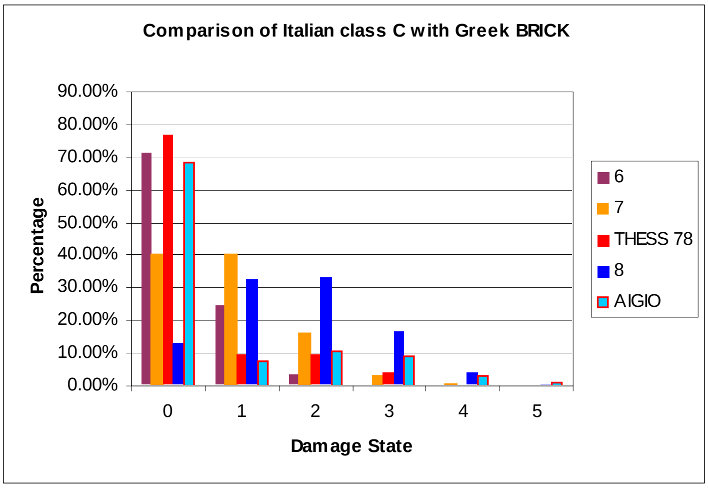

fig. 1b: Comparison of Italian and Greek damage data for brick masonry

- Different political approaches to post-earthquake recovery, more specifically in the way decisions for repair or reconstruction were made (recall that the economic damage index was the main criterion used in the Thessaloniki earthquake data).

5. 1ST LEVEL FRAGILITY CURVES

In order to use the DPMs presented in the previous section, these have to be converted to cumulative damage matrices and they have to include for each building type and damage state values of damaged buildings that should generally be proportional to the intensity, i.e. higher in the case of Aegion. Hence in Table 8 these matrices are presented and it is checked whether they satisfy the previous criteria.

Table 8: Cumulative DPMs

D	STONE 1		STONE 2		BRICK1		BRICK 2	
	Thess(2nd)	Aegion	Thess (2nd)	Aegion	Thess (2nd)	Aegion	Thess(2nd)	Aegion
0	100.00%	100.00%	100.00%	100.10%	100.00%	100.00%	100.00%	100.00%
1	35.64%	51.70%	47.71%	53.70%	24.00%	7.90%	21.11%	54.90%
2	22.77%	25.30%	33.59%	35.90%	14.75%	5.30%	11.11%	42.00%
3	9.89%	18.30%	19.47%	21.70%	5.50%	0.00%	1.11%	25.80%
4	5.00%	8.00%	11.07%	10.60%	0.50%	0.00%	0.00%	8.10%
5	1.17%	2.50%	4.58%	4.10%	0.25%	0.00%	0.00%	2.50%

It is seen that all data satisfy the aforementioned conditions except for the single-storey brick masonry buildings that include the out-of-trend data from Aegion, discussed in the previous section.

In view of the above, the following simple equation has been selected (among a number of others tried) to describe the 1st level fragility curve for single-storey and two-storey stone masonry buildings and two-storey brick masonry buildings:

$$P(D>DS/I) = e^{a+bI} \tag{1}$$

The resulting fragility curves for single-storey and two-storey stone masonry buildings are shown in figures 2, 3 and 4 respectively; note that numbers 1 to 5 correspond to the damage degree D.

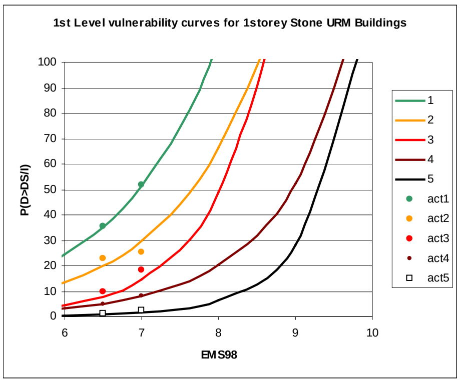

Fig. 2: Fragility curves for single-storey stone masonry buildings

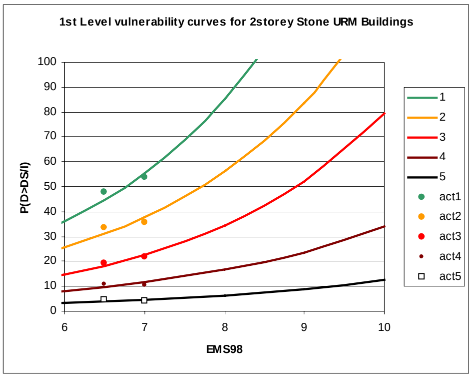

Fig. 3: Fragility curves for two-storey stone masonry buildings

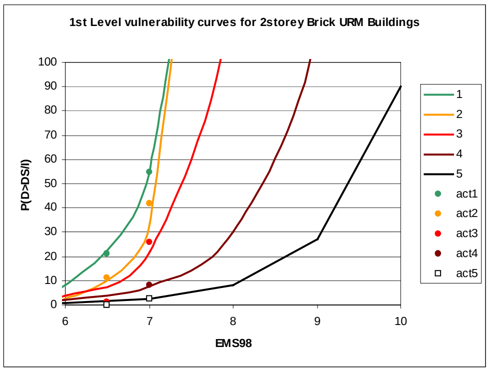

Fig. 4: Fragility curves for two-storey brick masonry buildings

Given that the rather simple curve fitting approach worked satisfactorily only in some cases (e.g. for two-storey stone masonry buildings, fig. 4), a more complex statistical approach has been subsequently adopted, by assigning a cumulative probability beta distribution to analytically describe the DPMs. This is supported by the fact that the data from the 2nd interpretation of Thessaloniki database and those from the Aegion database are in good agreement with the beta distributions shown in figure 5.

The beta distribution is defined as:

$$P(D \geq D_k) = 1 - P_\beta(k,a,b,r,t)$$

where: a, b, r and t are the parameters of the distribution; in particular a=0, b=6, t=4 (due to the large scatter of the Greek data). The parameter r is correlated to the mean damage factor μ_D (or MDF):

$$r = t(0.007\mu_D^3 - 0.0525\mu_D^2 + 0.2875\mu_D)$$

The mean damage factor μ_D is obtained by the vulnerability curve, as a function of the intensity I and the vulnerability index V_I:

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25\cdot V_I-13.1}{2.3}\right)\right]$$

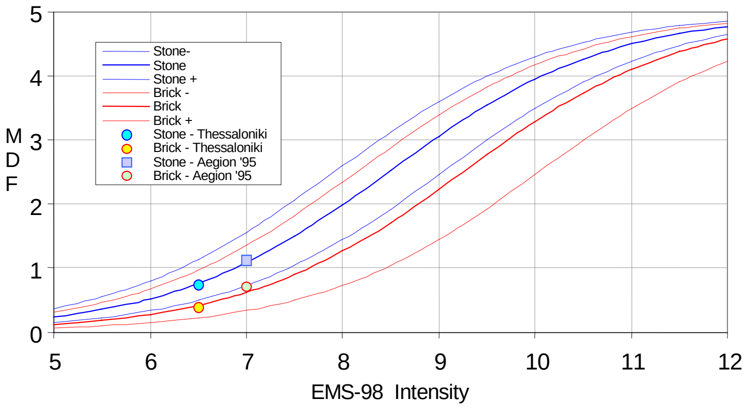

fig.5: Beta distributions for brick and stone masonry

In view of the very good match of the (corrected) Greek data with the mean curves for typologies "stone" and "brick" (fig. 5), the vulnerability indices for the Greek typologies, can be taken as the mean values for the aforementioned typologies Lagomarsino (2002):

- Simple stone masonry : $V_I = 0.74$
- Brick masonry walls: $V_I = 0.616$

The following figures show the resulting fragility curves.

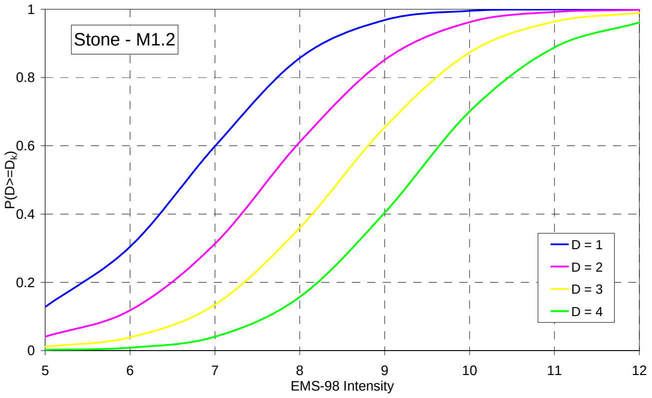

Fig. 6: Fragility curves for stone masonry buildings (beta distribution)

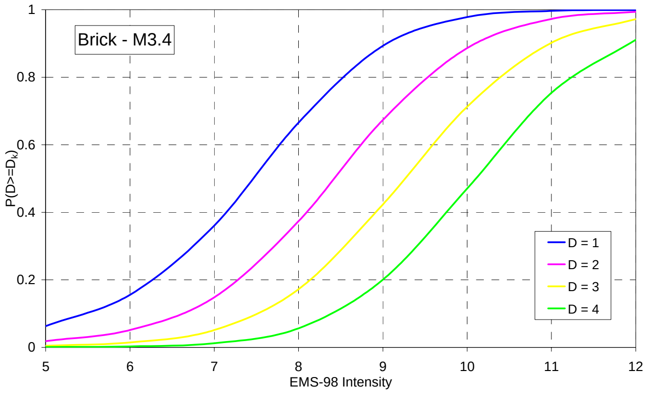

Fig. 7: Fragility curves for brick masonry buildings (beta distribution)

6. CONCLUSIONS

In the previous sections a methodology for the development of "1st level" fragility curves has been presented. The data used are purely statistical data from Greek earthquakes, the Thessaloniki 1978 and the Aegion 1995 events, with some additional data from the Pyrgos 1993 earthquake. They represent the first attempt nation-wide to develop empirical vulnerability relationships.

The resulting curves correlate the EMS98 intensity to the probability for a building type to exceed a particular damage state. These curves can be easily combined with the output of the earthquake risk scenarios and produce (with the aid of GIS technology) the expected damage (and ensuing monetary loss) for a specific hazard scenario.

The key unresolved issues are according to the authors the following two:

- The solution of the single-storey brick masonry buildings problem in the data from the Aegion earthquake which are statistical outliers (apparently due to the small sample in this case).
- A definitive determination of the intensities of the Thessaloniki and Aegion ground motions, which have been considered as 7 and 8 respectively, on the basis of reported information. A change in these values leads to a shift of the curves to the left or, in other words, in a higher vulnerability of the building classes.

Comparisons with vulnerability data from Italy (where most of the European studies in this field have been carried out so far) has shown significant similarities with the Greek data, on condition that a reassignment of intensities is carried out in the latter case. As expected, the smoother vulnerability curves resulted when beta-distributions were fitted to the empirical data.

7. Acknowledgements

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