DIRECT DERIVATION OF FRAGILITY CURVES FROM ITALIAN POST-EARTHQUAKE SURVEY DATA

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ABSTRACT :

A very complete and homogeneous database of post-earthquake building inspections, carried out after the main Italian events of the last 30 years, has been processed to derive fragility curves for 23 building typologies. The records (more than 91000) have been converted into a single damage scale with 5 levels of damage, plus the case of no damage. For each affected municipality a value of PGA and Housner Intensity (IH) has been evaluated using attenuation laws. Experimental data have been converted in damage probability matrices and then fitted through lognormal fragility curves, with an advanced nonlinear regression algorithm. The relative reliability of each point has been taken into account by applying the bootstrap technique. The significant concentration of experimental data at low levels of ground motion and the selected analytical expression determine the peculiar shape of some of the curves, with a very steep initial branch followed by an almost horizontal curve for increasing values of ground motion. Explanations and possible solutions are discussed.

KEYWORDS: fragility curves, vulnerability, seismic risk, post-earthquake damage data

1. INTRODUCTION

The frequent occurrence of earthquakes and their devastating power have drawn the attention to the evaluation of the seismic vulnerability of existing buildings and the characterisation of their seismic behaviour, which is strongly related to the amount of economic loss and the number of victims caused by the earthquake.
The relationships between ground motion and damage are typically expressed by means of fragility curves and/or damage probability matrices. Both provide the probability of exceeding various performance limit states, defined based on physical and socio-economic considerations, as a function of a selected seismic input parameter. Fragility curves can be obtained using different approaches and sources of information; a possible subdivision of the different procedures consists in [Corsanego, 1994; Rossetto and Elnashai, 2003; Calvi *et al.*, 2005]: empirical methods, based on statistical elaboration of damage data coming from observations; judgment-based methods, based on subjective expert judgement; analytical methods, based on evaluation of the seismic response through structural mechanics and hybrid techniques, combining different sources.
Empirical methods consist in a statistical elaboration of the data collected during post-earthquake surveys. They are the most realistic approach, since they allow to take into account all the characteristics affecting ground motion. Clearly the reliability of the results is in this case related to the available database of observed data, which must be homogeneous for what concerns constructional characteristics, ground motion source and soil conditions. At the same time, empirical data should cover a large range of ground motion and a sufficient number of building typologies. Even with these conditions satisfied, data coming from observations have an intrinsic uncertainty that cannot be removed and that is related to human errors during the survey phase. However, since data are then statistically averaged on a stock of many buildings, it can be reasonably assumed that the perturbation due to subjectivity is significantly reduced.

2. MAIN ELEMENTS FOR THE DERIVATION OF EMPIRICAL TYPOLOGICAL FRAGILITY CURVES

In this work, typological fragility curves have been derived from a very large dataset of empirical data, all

collected during Italian post-earthquake surveys. Typological fragility curves are meant as curves derived for groups of buildings which are expected to have a similar behaviour in case of an earthquake. A fragility curve represents the probability that a building, belonging to one of the selected building typologies, experiences a predefined level of damage, when subjected to a given level of ground motion. Three main elements hence are needed to define a vulnerability curve: the level of ground motion, represented through an appropriate parameter, a damage scale, with well defined levels of damage and a set of building typologies, for which fragility curves must be derived.
For describing the ground motion severity, two different parameters have been considered in this study: PGA and Housner intensity (IH). A single value of these ground motion parameters has been estimated for each municipality affected by one of the considered earthquakes, using the attenuation law of Sabetta and Pugliese [1987, 1996], for rock conditions (it is impossible to evaluate site effects for each building), with the parameters (magnitude and epicentral coordinates) of the earthquake of interest. The influence on results due to uncertainty related to the estimated PGA values has been studied [e.g. Rota, 2007; Rota *et al.* 2008]. Figure 1 shows the comparison between the values of PGA recorded during the earthquake by instruments and the values estimated using the Sabetta and Pugliese attenuation law. Notice that Figure 1 reports both the value from Sabetta and Pugliese on rock and the value amplified by 1.6, to account for the maxima local effects, according to the Italian seismic code [OPCM 3274, 2003], since the sites where PGA values have been recorded correspond to different soil conditions. The comparison of estimated and measured values can be considered satisfactory.

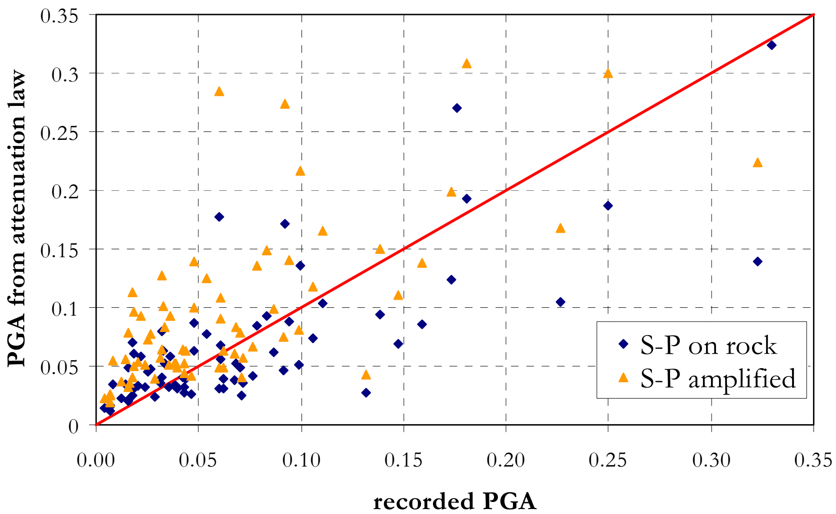

Figure 1 Comparison of recorded PGA and PGA evaluated with the Sabetta and Pugliese (S-P) [1987] attenuation law, on rock (blue diamonds) and amplified to account for site effects (orange triangles).

A damage scale similar to the one defined in the European Macroseismic Scale [Grünthal, 1998] has been adopted. It consists of five levels of damage (from DS1 to DS5) plus the case of no damage (DS0). In order to assign each building to one of the 5 damage levels, only structural damage to surveyed buildings have been considered and the maximum observed damage to vertical structure, horizontal structure and roof has been used. Since post-earthquake surveys were carried out using forms varying in time and hence they refer to different damage scales from earthquake to earthquake, in order to derive fragility curves based on data from all the available events, it has been necessary to convert the different scales into a unique one. The scheme reported in Table 2.1 has been followed, which is only slightly different from the one adopted by Dolce *et al.* [1999].
Buildings have been subdivided into different typologies, based on the typological classification proposed within the RISK-UE Project [2004], modified to account for the characteristics of Italian buildings and for the available data. 23 building typologies have been used, as indicated in Table 2.2. All the assumptions and considerations necessary to identify the selected building typologies are described in more detail in previous works [Rota, 2007, Rota *et al.*, 2008].

Table 2.1 Conversion of the damage levels of the different forms to the 5 damage states considered in this study

Post-earthquake surveys - damage description				
Damage state	Irpinia (1980)	Abruzzo (1984)	Marche (1997)	Pollino (1998) and Molise (2002)
DS1	Irrelevant – repair is not urgent	Slight	Null or slight 1/3 – 2/3	Slight < 1/3
	Slight – to be repaired		Null or slight > 2/3	Slight 1/3 – 2/3
				Slight > 2/3
DS2	Significant – to be partially evacuated - repairable	Significant	Medium-severe < 1/3	Severe < 1/3
DS3	Severe – to be evacuated - repairable	Severe	Medium-severe 1/3 – 2/3	Severe 1/3 – 2/3
			Medium-severe > 2/3	Severe > 2/3
DS4	Very severe – to be evacuated and demolished	Very severe	Very severe – collapse < 1/3	Very severe < 1/3
			Very severe – collapse 1/3 – 2/3	Very severe 1/3 – 2/3
DS5	Partially collapsed – to be demolished	Destruction	Very severe – collapse > 2/3	Very severe > 2/3
	Destroyed			

Table 2.2 Selected building typologies

Label	Building class	No. of storeys
MX1	Mixed	1-2
MX2	Mixed	≥3
RC1	Reinforced concrete – seismic design	1-3
RC2	Reinforced concrete – no seismic design	1-3
RC3	Reinforced concrete – seismic design	≥4
RC4	Reinforced concrete – no seismic design	≥4
IMA1	Masonry – irregular layout – flexible floors – with tie rods and/or tie beams	1-2
IMA2	Masonry – irregular layout – flexible floors– w/o tie rods and tie beams	1-2
IMA3	Masonry – irregular layout – rigid floors – with tie rods and/or tie beams	1-2
IMA4	Masonry – irregular layout – rigid floors - w/o tie rods and tie beams	1-2
IMA5	Masonry – irregular layout – flexible floors – with tie rods and/or tie beams	≥3
IMA6	Masonry – irregular layout – flexible floors– w/o tie rods and tie beams	≥3
IMA7	Masonry – irregular layout – rigid floors – with tie rods and/or tie beams	≥3
IMA8	Masonry – irregular layout – rigid floors - w/o tie rods and tie beams	≥3
RMA1	Masonry – regular layout – flexible floors – with tie rods and/or tie beams	1-2
RMA2	Masonry – regular layout – flexible floors – w/o tie rods and tie beams	1-2
RMA3	Masonry – regular layout – rigid floors – with tie rods and/or tie beams	1-2
RMA4	Masonry – regular layout – rigid floors – w/o tie rods and tie beams	1-2
RMA5	Masonry – regular layout – flexible floors – with tie rods and/or tie beams	≥3
RMA6	Masonry – regular layout – flexible floors – w/o tie rods and tie beams	≥3
RMA7	Masonry – regular layout – rigid floors – with tie rods and/or tie beams	≥3
RMA8	Masonry – regular layout – rigid floors – w/o tie rods and tie beams	≥3
ST	Steel	All

3. AVAILABLE DAMAGE DATA

The data used in the current study have been collected during post-earthquake surveys after the earthquakes of Irpinia (1980), Abruzzo (1984), Umbria-Marche (1997), Pollino (1998) and Molise (2002). A total of 164000 survey forms were made available to the authors. Since for each of the considered events a different survey form has been used, in order to statistically process all the data together and obtain fragility curves, it has been necessary to homogenise the different datasets, identifying common building typologies and a common damage scale. The hypotheses used for the homogenisation can be found in [Rota, 2007]. During this process, some data have been disregarded due to important information missing, leading to a database of approximately 150000 buildings. Such amount of data has been further reduced based on considerations on the issue of completeness of the surveys, which are often carried out only on request and hence include only damaged buildings. In order to avoid the use of a significantly biased sample, only data related to Municipalities surveyed for at least 60% (as compared to ISTAT census data [2001]) have been considered. The effect of this hypothesis on the derived fragility curves has been tested and compared to other assumptions and it has finally proven to be satisfactory.
At the end, a database of more than 91000 buildings, constituting a complete and statistically sound sample, has been processed to derive fragility curves. The available data are plotted in Figure 2, subdivided into the 23 considered typologies and the 10 PGA intervals. It can be noticed that most of the data refer to low values of ground motion.

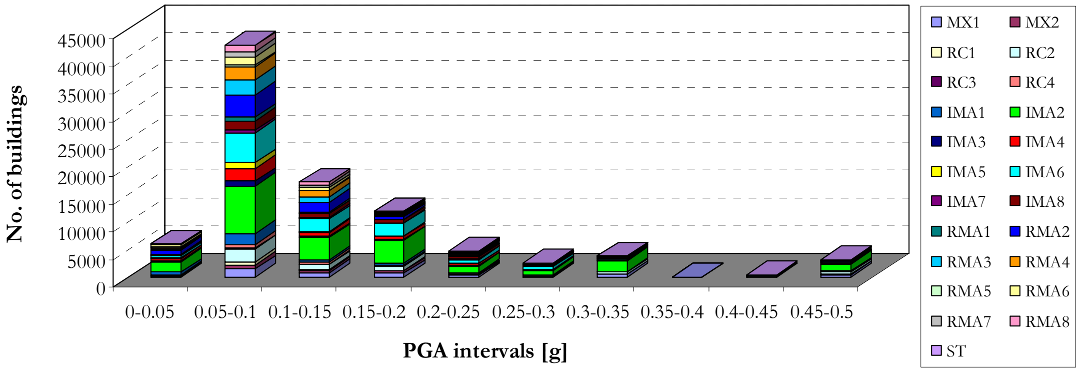

Figure 2 . Subdivision of the available data into the 23 building typologies and the 10 PGA classes selected.

4. DERIVATION OF FRAGILITY CURVES

The first step towards the derivation of fragility curves consists in extracting damage probability matrices (DPMs) from the empirical data, which represent, for each building typology and for each ground motion interval, the experimental probability of occurrence of the different damage states [Whitman *et al.*, 1973]. A Visual Basic Code has been developed and used to extract the DPMs, for each selected building typology, from the database of empirical data.
The experimental data, in the form of DPMs, have been then processed to get the parameters of an analytical function fitting the data. In particular, the lognormal probability distribution has been selected, since it has been adopted for describing fragility curves by several other authors [e.g. RISK-UE, 2004; Singhal and Kiremidjian, 1996; FEMA, 1999; Spence *et al.*, 2003; Sarabandi *et al.*, 2004; King *et al.*, 2004; Kappos *et al.*, 2006]. Such probability distribution is completely described by two parameters: μ and σ. Finding these two unknown model parameters is an optimisation problem, which has been solved using a nonlinear regression, through the iterative linearised damped least-squares method of Levenberg and Marquardt [Levenberg, 1944; Marquardt, 1963]. The subdivision of the available data into 23 building typologies and 10 ground motion classes obviously reduces the size of some samples and hence also the reliability of the estimated damage distribution, which strongly depends on the sample size. The bootstrap technique [Efron and Tibshirani, 1994] has been implemented to evaluate the uncertainty associated to the probability of each damage state for each typology and each ground motion level. The inverses of the estimated standard deviations have been then used as weights

in the derivation of fragility curves.
The parameters μ and σ of the lognormal distribution have been evaluated for each building typology and for each damage level using this procedure, obtaining fragility curves both in terms of PGA and IH. The results of the curves in PGA will have been already published in several previous works [e.g. Rota *et al.*, 2006; 2008] and will not be reported here. The results of the curves in Housner Intensity, instead, are summarised in Table 4.1. Notice that the results of some of the selected building typologies are missing, as well as the results of the damage level DS5 for some cases. This is due to the fact that only a reduced sample of data was available for these cases and hence the parameters obtained for the lognormal distributions were not statistically meaningful.

Table 4.1 Parameters of the lognormal distribution for the fragility curves in Housner intensity

Label	DS1		DS2		DS3		DS4		DS5	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
MX1	1.60	4.36	7.69	5.88	13.64	8.95	11.16	5.01	9.13	2.90
MX2	1.20	5.67	6.83	4.44	6.97	3.18	9.70	4.01	8.91	2.58
RC2	5.30	3.80	11.04	4.83	9.26	2.85	7.84	1.85	-	-
RC4	4.25	2.91	7.90	3.11	7.84	2.55	8.28	2.06	-	-
IMA1	-9.94	13.23	10.23	17.01	12.15	10.20	10.89	5.82	9.41	3.03
IMA2	-7.97	9.30	2.31	13.80	8.23	15.27	11.57	10.64	11.27	6.36
IMA3	-1.98	13.92	11.99	11.25	14.12	9.14	13.41	6.21	-	-
IMA4	-7.18	11.33	4.27	6.26	6.15	5.11	6.89	3.43	6.99	2.34
IMA5	-8.92	10.36	3.10	5.94	4.79	2.92	13.65	7.85	10.54	3.91
IMA6	-7.28	8.11	2.37	10.65	5.43	6.48	7.30	4.63	8.98	3.93
IMA7	0.93	4.15	3.58	1.83	4.56	1.90	7.29	3.08	8.32	2.50
IMA8	-5.84	8.58	2.73	4.23	3.92	2.53	5.27	2.26	6.58	2.12
RMA1	0.89	8.01	15.56	12.26	13.59	7.69	10.39	3.59	6.31	0.95
RMA2	-9.01	14.89	7.42	11.16	11.72	10.91	14.21	8.77	11.85	5.06
RMA3	6.84	14.80	11.51	6.55	11.27	5.12	8.95	2.98	7.19	1.65
RMA4	0.37	16.33	18.50	15.35	16.05	9.75	12.77	5.43	8.53	2.27
RMA5	-0.14	8.81	7.98	9.60	13.20	9.08	9.22	3.36	6.77	1.36
RMA6	-2.39	6.56	3.69	3.46	4.97	3.18	6.23	2.81	9.24	3.69
RMA7	3.47	5.06	10.05	7.07	7.58	3.39	11.50	4.67	8.98	2.61
RMA8	-0.61	11.59	6.99	7.61	7.25	4.47	7.63	2.98	8.60	2.73
MX1	1.60	4.36	7.69	5.88	13.64	8.95	11.16	5.01	9.13	2.90
MX2	1.20	5.67	6.83	4.44	6.97	3.18	9.70	4.01	8.91	2.58

5. DISCUSSION OF RESULTS

Two examples of the obtained fragility curves in Housner intensity are reported, in order to show the effect of the applied weights. Figure 3 shows the curves in IH obtained for the building typology IMA4, while Figure 4 shows the curves for RMA1. As expected, the effect of the weights determined through the bootstrap technique is more significant for small and low quality samples: it can be seen indeed that for the case of IMA4, with 4455 buildings, the effect is less noticeable than for the case of RMA1, with only 1295 buildings. In this latter case, the curves of the highest damage states, for which less data are available, are strongly affected by the weights, which determine a change of curvature with respect to the non-weighted case. Notice that in the right part of the figures, showing the weighted curves, there are some error bars associated to the experimental points, which represent the relative value of standard deviation evaluated using bootstrap for each point. The curves have been plotted up to a value of I_H = 80 cm, which corresponds approximately to a PGA of 0.3 g, considered the range of interest for Italy.

By observing the fragility curves (reported for all typologies and both PGA and IH in [Rota, 2007]) some comments on the obtained results can be made. Most of the proposed fragility curves, except for those derived for reinforced concrete structures, present a very steep branch (nearly vertical) close to the origin. This indicates a very high probability of slight damage even for very low values of PGA. This behaviour is partly related to the selected analytical expression, i.e. the lognormal distribution and, in particular, the steep initial branch is due to very low values (often negative) of the mean parameter of the distribution, as directly derived from the available observed post-earthquake damage data. These data show that several building typologies, and in particular the most vulnerable types of masonry structures, experience a slight level of damage (typically of grade DS1) for very low values of ground motion, and possibly even in the absence of an earthquake. This pre-existing damage is mainly due to the poor conditions of many bad quality masonry buildings in Italy, which lack proper maintenance and hence can show some pre-existing damage also before the earthquake strikes [Angeletti *et al.*, 2002]. These already existing structural or non structural defects can then be easily aggravated by the earthquake. Di Pasquale and Orsini [1997] and Di Pasquale *et al.* [2005] also reported similar observations.

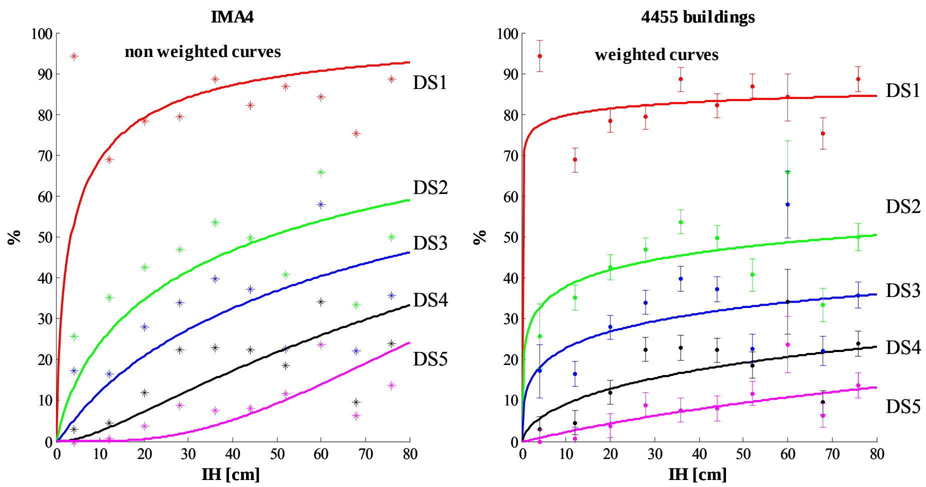

Figure 3 Comparison of non weighted and weighted fragility curves in IH for IMA4.

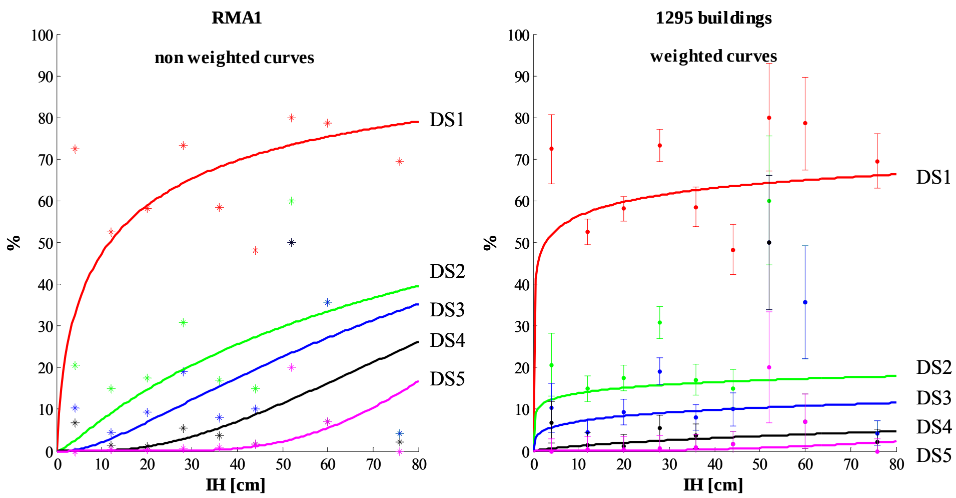

Figure 4 Comparison of non weighted and weighted fragility curves in IH for RMA1.

5. CONCLUSIONS AND FURTHER DEVELOPMENTS

Fragility curves have been directly derived from damage data collected during post-earthquake surveys, after the main Italian earthquakes of the last thirty years, for several building typologies characteristic of the Italian building stock. These curves have been obtained from a very complete and homogeneous database, consisting of many data, all collected in Italy. This is a significant advantage over most other datasets used in the literature, which are either referred to a single event and hence small [e.g. Braga *et al.*, 1982] or obtained assembling data from earthquakes in different areas of the world [e.g. Rossetto and Elnashai, 2003] and hence heterogeneous.
A unique damage scale has been used for deriving the curves, with five levels of damage plus the case of no damage. Since different survey forms have been used after each event, the available data have been homogenised to eliminate differences. Curves have been derived using both PGA and Housner intensity as a ground motion parameter. To obtain fragility curves, experimental points have been fitted with lognormal distributions, using appropriate weights to account for the reliability of each point, evaluated using bootstrap.
Some of the obtained fragility curves, particularly for low levels of damage, show a peculiar shape, with a very steep initial branch and an almost flat behaviour for increasing ground motion. This is due to the selected analytical function, the lognormal distribution and also to the very high concentration of observed damage data at low values of ground motion. This results in a large standard deviation of the lognormal distribution and hence provides curves that increase only slightly as the ground motion increases, never reaching the cumulative probability value of 1 in the considered ground motion interval. This effect is less pronounced for the higher damage levels, since observed collapses have occurred for higher values of ground motion.
Since one would physically expect a higher dependence of vulnerability on ground motion, it could be possible to introduce additional points, determined based on expert judgement and physical constraints, in order to modify the shape of the curves. For example, engineering judgement suggests that for a PGA higher than 1g, practically 100% of the existing buildings would sustain significant damage. This additional information can be assigned a very high reliability and may hence be able to ensure that the probability of reaching the different damage levels increases more significantly with ground motion severity. Clearly it is not straightforward to determine the reliability to be assigned to these points and hence further analyses are required.
Other future developments of this methodology should consider the addition of more data related to the higher ground motion levels. Moreover, the use of probability distributions other than the lognormal one should be explored in order to study the dependence of results on the assumed analytical expression fitting the data. Also, the possibility of defining some regional behaviour modification factors influencing building vulnerability could be considered.

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