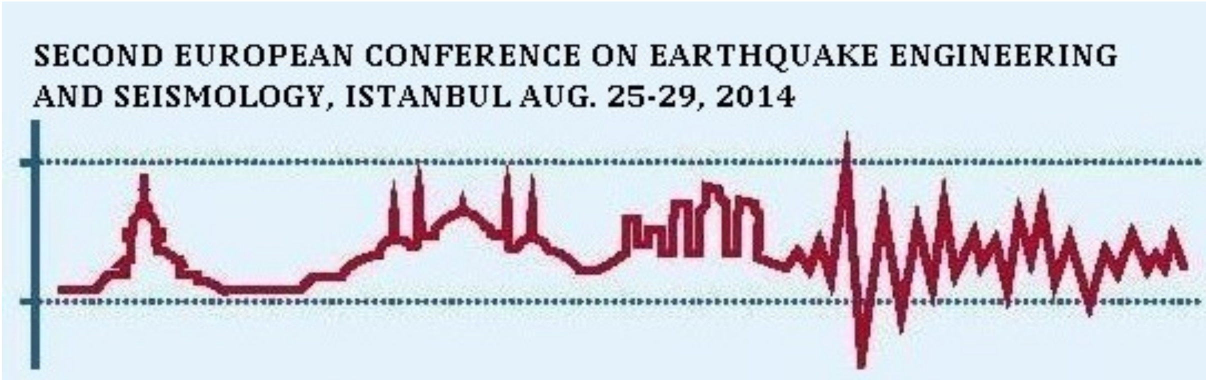

HARMONIZATION OF VULNERABILITY CURVES FOR MASONRY BUILDINGS

ANDREA SPILLATURA[1], EMILIA FIORINI[2], PAOLO BAZZURRO[3] and DOMENICO PENNUCCI[4]

ABSTRACT

The definition of the vulnerability of a building is a key step in the estimation of seismic risk. Several studies on the subject are available in literature, proposing vulnerability curves for a variety of building typologies and structural configurations. However, studies from different authors most often adopt different basic assumptions, especially in terms of limit state definition, and a unified view of vulnerability based on published material is not available yet.

This study gathers published vulnerability curves on masonry buildings typical of Italy and Southern Europe and makes an attempt to harmonize the intensity measure parameters in order to produce a family of curves that can be compared and contrasted. We also compute a best estimate of such curves using an equal-weight averaging scheme. In addition, to mean damage ratio curves we also provide the dispersion around the mean in terms of the 10^{th} and 90^{th} percentile curves for a variety of unreinforced masonry building classes, depending on material of construction and height. This family of curves can be used to assess the robustness of vulnerability curves used by catastrophe risk models.

Possible applications of these findings in the field of seismic risk are also discussed.

INTRODUCTION

Seismic loss estimation heavily relies on the definition of realistic vulnerability curves, in which a specific loss, often expressed as a ratio of repair losses to the building replacement cost, is related to a measure of the ground motion intensity (such as peak ground acceleration or spectral acceleration). These curves are used in the vulnerability module of catastrophe risk models for assessing seismically-induced losses to portfolios of buildings. However, the robustness of the vulnerability functions contained in these models is very difficult to assess. The reason for this difficulty is in part related to the body of the literature on the topic, which is fragmented in a large number of narrowly-focused studies that use different assumptions and produce functions in different formats, and in part because these models are often black boxes. This study makes an attempt to provide a family of curves that are as uniform as reasonably possible.

[1] MSc, Understanding and Managing Extremes (UME) school, Pavia, andrea.spillatura@umeschool.it
[2] Dr, EUCENTRE, Pavia, emilia.fiorini@eucentre.it
[3] Prof., University Institute for Advanced Studies (IUSS), Pavia
[4] PhD, Guy Carpenter, Milan, domenico.pennucci@guycarp.com

In the engineering field, however, most studies provide fragility curves for specific building damage states, such as collapse, rather than vulnerability functions. The fragility functions, which provide the probability that a building will exceed a given damage state for different levels of ground motion intensity, do not carry the units of loss but are related to damage states whose repair cots can be defined via so-called consequence functions. Hence, fragility curves are stepping stones to derive vulnerability curves. The fragility functions available in the literature are derived either empirically (i.e., based on real damage data), or analytically (based on engineering analyses such as Non-Linear Time history Analysis or Non Linear Static Analysis), or based on expert judgment, or on a combination of some or all of these techniques (i.e., Hybrid approach). In addition, a fragility study can consider different types of structures, in terms of material (i.e., masonry, reinforced concrete, precast concrete…) and/or structural typology (e.g., moment resisting frame, shear wall structure and frame/shear wall dual structure).

This study gathers published literature on vulnerability of masonry structures in Italy and Southern Europe and creates a vulnerability curves database that is processed for the definition of best estimate curves and of the variability across curves. This exercise requires the harmonization of the intensity measures of different vulnerability curves. The process is explained below.

LITERATURE REVIEW

An initial database of Fragility Functions has been selected starting from the existing databases of GEM and Syner-G projects (cf. [22], [29], [30]), which were further supplemented by other studies. The following list briefly summarizes the main characteristics of the buildings included in the studies considered here:

1. Structural type (Masonry bearing walls);
2. Material Type (stone, fired bricks…);
3. Cladding
4. Height

The review has led to some considerations, which are in order:

1. Not all fragility functions are based on the same damage scale (DS), where the damage represents the schema used to distinguish damage states of different severity ranging from no damage to collapse.
2. Not all fragility functions use the same intensity measure (*IM*) (e.g., peak ground acceleration or spectral acceleration) to gauge the level of the ground shaking.
3. Some fragility studies have produced functions that are inconsistent with basic probability axioms (i.e. the fragility functions for different damage states cross one another) and, therefore, present additional challenges for integration.
4. Consequence functions, which, as mentioned before, provide an estimate of the loss associated to a certain damage state, can be evaluated empirically, from real damage data, or through expert judgment. As the loss is defined as function of a damage state, the description of the damage states within a given damage scale affects the results.
5. The loss can be expressed in absolute terms (i.e., US Dollars or Euros), or in relative terms as a fraction of the replacement cost of the building. This fraction is called the damage or cost ratio (CR). The main advantage for using this ratio rather than the absolute value of the repair cost is that it allows to easily compare losses occurred in buildings of the same type but with different characteristics (e.g. area), therefore making the management of replacement costs more straightforward.

Overall, this review identifies eleven studies for masonry buildings suitable to the need of this work. Each study includes more than one family of functions. A single study may comprehend functions developed for different types of structures, different levels of detailing, different IMs and several damage scales. These nonhomogeneous definitions of damage dictate the need of processing the database in order to come up with results that can be compared and discussed.

Table 1 summarizes the main characteristics of the selected studies.

Table 1- List of studies included in the present work and their description

Reference	Description
Ahmad et al. (2010)	Analytical study. Reinforced Concrete Frame (Bare and Infilled Frames, considering regular and irregular plan distribution, Ductile or non-Ductile behavior) and Masonry buildings (stone and brick masonry buildings, differentiated by voids percentage: high or low). Curves distinguished by number of stories (2, 5, 8 for RC and 2,4 for Masonry). Analysis Method: Displacement Based Earthquake Loss Assessment methodology. Prototype buildings are designed to simulate the existing Euro-Mediterranean portfolio. Ten natural accelerograms from USA and IBC-2006 rock spectra. Damage Scale: HAZUS (1999). Intensity Measure: PGA.
Lagomarsino and Giovinazzi (2006)	Hybrid study: combination of a Macro-seismic Method (Giovinazzi and Lagomarsino, 2001) and a Mechanical Approach (Capacity Spectrum Method). Masonry and Reinforced Concrete buildings. Building detailed by Code Level (RC frames), Material typology (Masonry) and height. In the paper, the authors provide their own conversion relationship to translate the EMS98 Macro-seismic Intensity into PGA. The curves are applicable to Europe. Damage Scale: EMS-98. Intensity Measure: EMS-98.
Braga et al. (1982)	Empirical study. Damage Data: Italian Earthquakes prior to the 1982. The buildings subdivided into three categories (A, B and C) according to their vulnerability, estimated from post-earthquake surveys. The C category comprehends the less vulnerable buildings, i.e. Brick Masonry and Reinforced Concrete buildings. Damage Scale: MSK. Intensity Measure: MSK.
Sabetta et al. (1998)	Empirical study (same details as Braga, 1982). The authors suggest their own procedure to derive PGA from MSK intensity. The fragility curves are expressed in terms of Damage Probability Matrix.
Di Pasquale et al. (2005)	Empirical study. RC buildings and Masonry. There are not specifications related to code, masonry types or buildings heights. As IM, MCS Scale is adopted. The fragility curves are expressed in terms of Damage Probability Matrix. Damage Scale: EMS-98 Intensity Measure: EMS-98.
IZIIS	Trendafiloski G. (2003) and Nocevski N. (1993) developed the hybrid curves included in this assembly. The methodology adopted for the derivation of fragility curves is the one deepened by Lagomarsino and Giovinazzi(2006), but applied to regional data. As already seen in Kappos (2003, 2006) the curves can be considered as applicable to the Euro-Mediterranean Regions.
UPAT (2011)	Analytical study. Developed within the Syner-G project, these fragility curves are applicable to Europe and refer to different types of masonry buildings. Non Linear Static approach. Two different options on the modelling of openings are investigated. The height level is specified. Damage Scale: EMS-98. Intensity Measure: PGA.
Rota et al. (2010)	Analytical study. Developed by means of Non Linear Dynamic Analyses for Masonry Low Rise Italian buildings (3-storeys masonry building located in Benevento constructed in 1952). The accelerograms adopted are from online strong motion record databases (www.isesd.cv.ic.ac.uk/, peer.berkeley.edu/smcat/, db.cosmos-eq.org/). Damage Scale: HAZUS. Intensity Measure: PGA.

DATABASE PROCESSING AND LOSS CURVE DERIVATION

The processing of the curves gathered in the database, required for the definition of best-estimates damage ratio curves, is based on the following three steps:

- Harmonization of the intensity measure (different studies most often use different intensity measures, such as PGA, Sa, Sd, MMI, etc.)
- Definition of consequence function to correlate damage limit state to economic losses

Each individual step of the procedure is discussed in the following paragraphs.

IM Harmonization Criteria

A most important step in this work has been the selection of equations that allow converting from PGA to macroseismic Intensity, MI (Ground Motion to Macroseismic Intensity Conversion Equations) and from MI to PGA (Macroseismic Intensity to Ground Motion Conversion Equations). Several equations exist that convert PGA to MI, while fewer equations are available for the conversion from MI to PGA. The conversion equations are based on regression analysis of datasets pairing PGA from recording stations with nearby values of MI. In the selection of a conversion equation, it is important to consider the region for which it was developed, the dataset used and the type of regression utilized. Since the equations are regression relationships between MI and the quantitative measure of interest, the more the data available for each MI value, the more reliable the equations will be (other things being equal in the GM-MI pairings).

The literature review on this subject has led to the preliminary selection of four different relationships. The choice is based on the publication year (typically more recent studies have larger database available), the MI scale utilized, the type of regression used (modern equations that allow the statistical conversion between MI and PGA in both directions are favored), and the spread of their use in Italy. Table 2 summarizes the main characteristics of the selected equations (for equations please refer to the original papers).

Table 2 – Main IGMCEs characteristics

Author/Region	**Units**	**MI Interval**	**PGA Interval [g]**
Margottini et al. (1992), Italy	cm/s^2	$4<I_{MI}<8$	0.02<PGA<0.227
Faenza and Michelini (2010), Italy	cm/s^2	$4<I_{MI}<8$	0.008<PGA<0.287
Worden et al. (2012), USA	cm/s^2	$I_{MI}<9\text{-}9.5$	PGA<0.747

Two different approaches for the conversion to PGA of the consequence functions originally developed in MI were explored:

1. Application of different IGMCEs consistent with the MI type of the original study;
2. Selection of one ground motion intensity measure to MI equation and application to all the studies, regardless of the MI scale originally utilized.

It was decided to consider all the MI scales as equivalent and perform the conversion according to the most suitable regression relationship. This choice was supported by the fact that, according to Musson et al. (2009), for the intensity scales considered in this work the variability of MI selection tends to outweigh the differences between scales. This viewpoint was shared by Stucchi (2014)[5].

Among the four equations originally considered, the one developed by Worden (2010) was adopted. This decision is mainly due to the following considerations:

- The relationships of Margottini et al. (1992) have been replaced by the most recent study of Faenza and Michelini (2010).
- The equation of Faenza and Michelini (2010) is tailored for Italy and relatively recent, but its applicability, is limited to a MI level of 8, a level of damage which is caused, on average, by PGA levels around 0.3g. This level of PGA is too low to be used in the conversion of the consequence functions. On the contrary, Worden (2012) used a large dataset of MMI data from California and it is applicable to higher intensity levels. In particular the conversion equation can be considered reliable until MMI = 9, which corresponds to a PGA of around 0.7 g.

The previous lines describe the procedure to translate MI into PGA; since the selected expressions are orthogonal, they can be adopted also for the translation in the other direction, i.e. from PGA to MI.

[5] Stucchi, M. (2014). Personal communication, February.

For the cases in which the IM is expressed in terms of the Spectral displacement, $S_d(T)$, the following procedure has been followed to derive PGA.

- PGA and $S_a(T_y)$ have been derived from the "Attenuation Relationships Plotter" of OpenSHA utilizing Boore and Atkinson(2008) which is applicable to the Italian tectonic environment. A Rock Site soil has been hypothesized with $V_{s,30}$=800 m/s (according to NTC08) together with an unknown style of faulting. About Magnitude and Distance, the following values of magnitude and distance have been selected:
  - Distance: 10 and 25 km;
  - Magnitude: 6, 6.5 and 7.
- For all the possible Magnitude-Distance pairs, the ratio $S_a(T)/PGA$ has been evaluated, and the average of them has been taken as reference.
- From the following relationship the PGA can be evaluated, knowing S_d, and the ratio $S_a(T)/PGA$:

$$\frac{S_d(T)}{PGA} = \left(\frac{T}{2\pi}\right)^2 \frac{S_a(T)}{PGA} \qquad (1)$$

Consequence Functions

The damage or loss ratio is defined as the ratio of repair cost to building replacement cost and can be evaluated via expert judgment or empirical post-earthquake studies of loss data. A consequence function (which assigns a CR to a certain damage level), can be derived from damage data related to a particular country and/or can be sensitive to the "local" knowledge of the expert that has developed it. Therefore, two different consequence functions that use the same damage scale (i.e. the same definition of damage states) may have vastly different damage ratios associated with the same damage state (cf. Hill and Rossetto, 2008 [13]).

Overall, two approaches are possible to define damage functions:

1. Use the consequence function related to the damage scale according to which the fragility curve is developed and transform each of the fragility curves into the corresponding damage function.
2. Use only one consequence function and "translate" the damage states of all the other damage scales adopted in the development of other fragility functions into those of the damage scale for which the considered consequence function has been defined.

The main advantage of the second approach would be that the consequence functions developed only for Italy could be used. The main shortcoming, however, is its qualitative nature (cf. Rossetto and Elnashai, 2003) that makes impossible a consistent translation of fragility curves from a damage scale to another. This drawback made us opt for the first approach and, therefore, the fragilities were converted into vulnerability functions using different consequence functions for each damage scale. Unfortunately, this procedure caused the exclusion of some studies characterized by uncommon damage scales. In these cases, it was not possible to find or derive consequence functions because of the peculiarities on the damage states definition.

RESULTS

Several damage curves have been generated for the following structural characteristics: (i) Material of Construction (masonry), (ii) Number of stories (low/medium-high rise). Each curve is expressed both in terms of PGA and in terms of MI. The code level classification has not been implemented for masonry buildings because the investigated studies did not consider it.

A set of representative examples of vulnerability curves for masonry buildings are shown and discussed in the following lines. For a more comprehensive collection of the damage ratio curves please refer to Spillatura et al. (2014). The cited study includes also reinforced concrete curves together with an "a priori" weighting criteria with the aim to achieve more reliable and objective results

Figure 1 and Figure 2 show the homogenized vulnerability curve for mid/high rise (with three or more stories) masonry buildings and for low-rise (one or two stories) masonry buildings, respectively. The axes are PGA and Modified Mercalli Intensity, MMI, as intensity measure. For PGA higher than about 0.8 g the chart is shaded to underline the reduced confidence of the relationships in this range of IM. This is due to the equation adopted for the IM conversion (i.e. Worden, 2012) that is reliable until MI of around 9/9.5 (i.e., between values of PGA ranging from 0.7g and 1.0g).

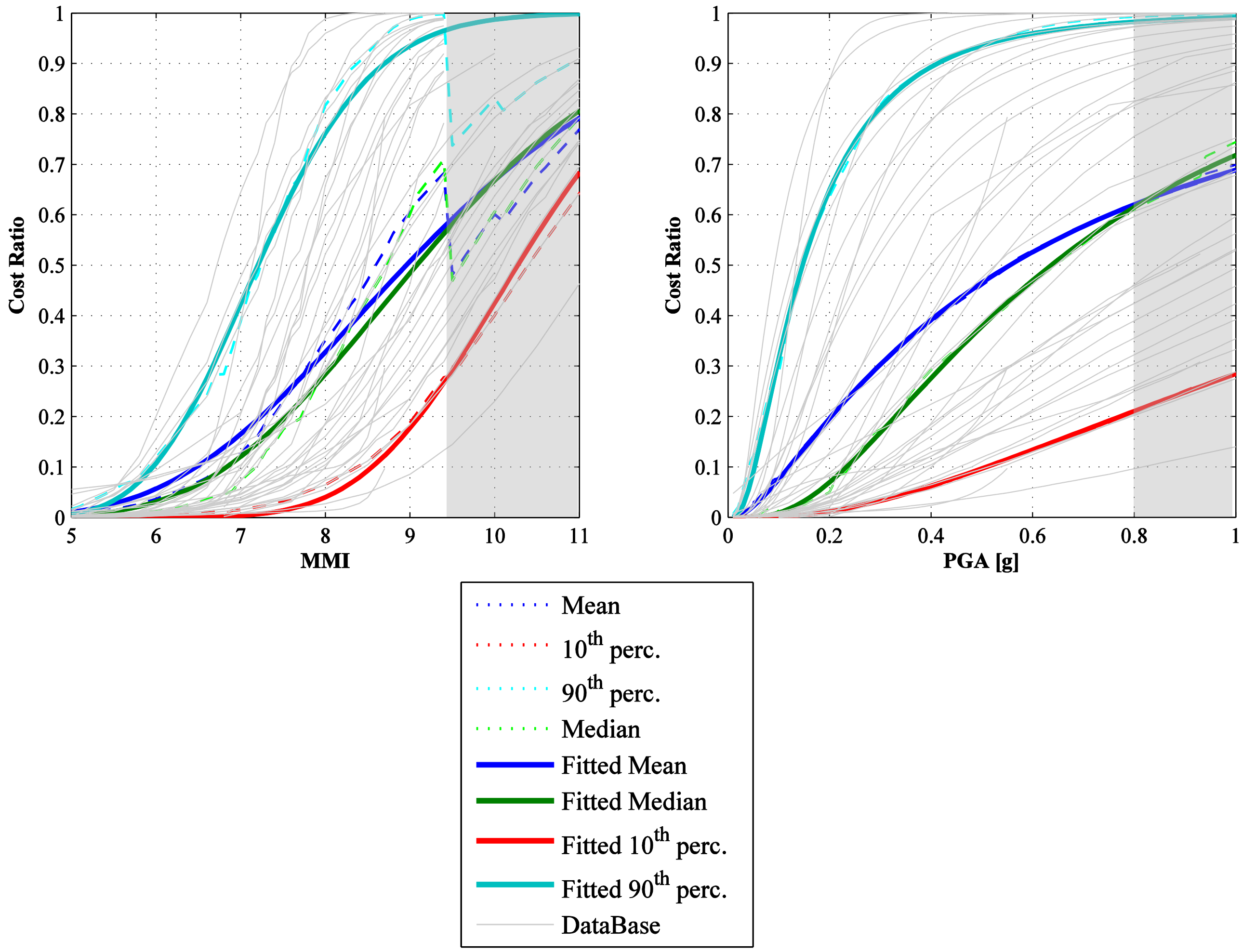

Figure 1 – Masonry Mid/High Rise Buildings

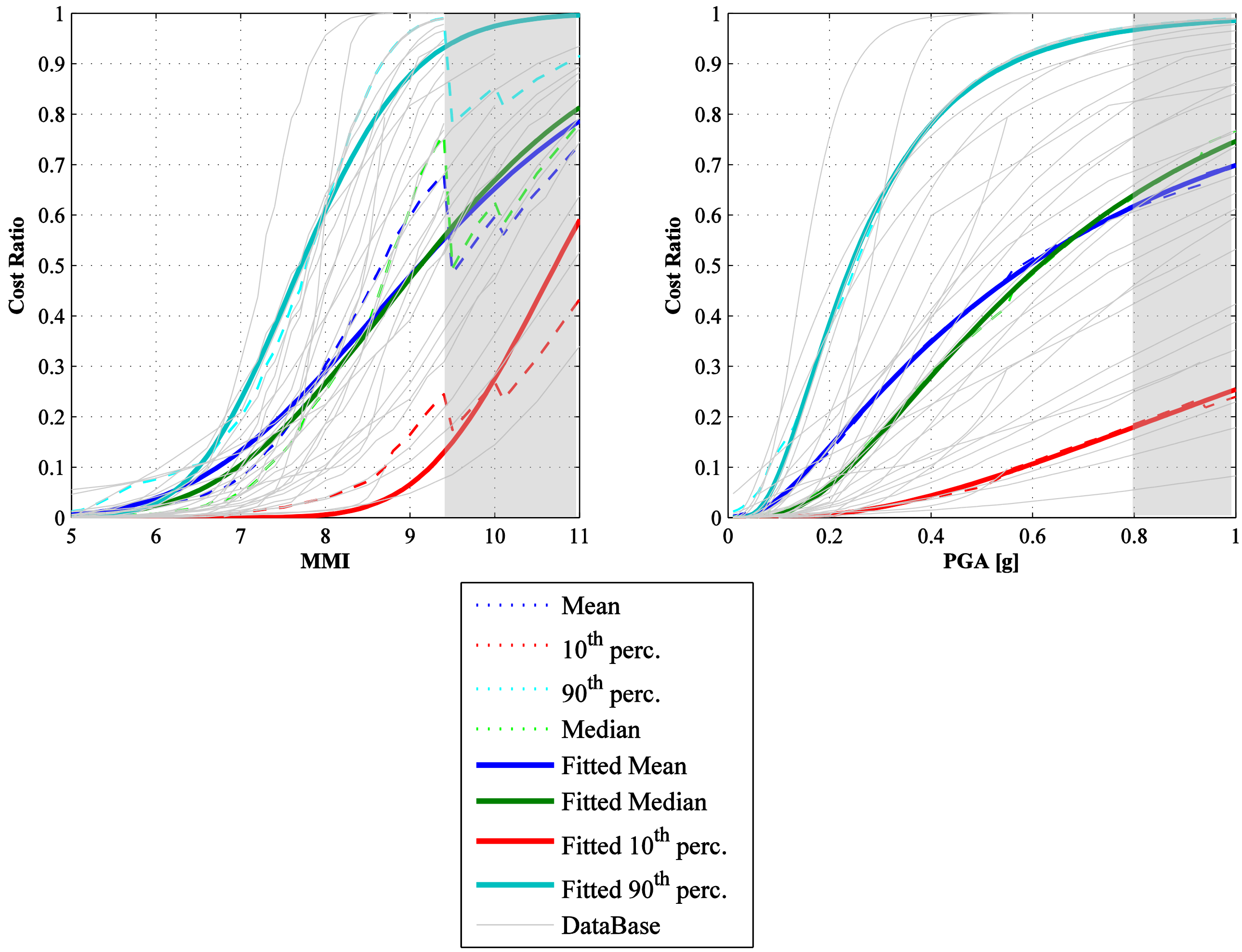

Figure 2 – Masonry Low Rise Buildings

In addition to the family of vulnerability curves, Figures 1 and 2 show also some summary statistics curves, namely the mean, the median, and the 10^{th} and 90^{th} percentile curves. All the summary statistics curves were derived assuming that each study had the same weight, namely the same credibility. This is a limitation not supported by the evidence that will be overcome in a future research study.

Overall, the general consistency of the mean curves associated to different levels of code provisions and the different construction material has been evaluated and results have been found to be realistic and in line with engineering expectations.

CONCLUSIONS

The main scope of this study is to offer a unique and consistent collection of vulnerability curves for use in seismic risk applications. The work does not produce new vulnerability curves from scratch to be added to the already various and populated existing literature, but it rather re-elaborates and harmonizes what has already been produced in the past by other researchers to produce a single, best estimate damage curve for each building typology and its variability. The proposed damage curve is expressed in terms of economic loss, rather than probability of reaching a certain limit state, so that implementation in seismic risk applications is facilitated.

The final output of the study is a set damage ratio curves for masonry buildings using PGA and MMI as intensity measures. The dispersion around the mean curve, which is computed in terms of 10^{th} and 90^{th} percentile curves, is quite large.

Given the format of the proposed curves (in terms of economic loss ratios) the authors believe that the applicability of this study into seismic risk application is straightforward and can represent a useful aid to risk engineers for the generation of new vulnerability modules or the validation of existing ones. The already cited paper (Spillatura et al., 2014) applies the same methodology to reinforced concrete buildings.

ACKNOWLEDGEMENTS

This work has been partially funded with a research grant by Guy Carpenter, which is gratefully acknowledged by the authors.

REFERENCES

[1] Ahmad N., Crowley H., and Pinho R. (2010), Analytical fragility functions for reinforced concrete and masonry buildings and building aggregates, UPAV-Internal Report.

[2] ATC-13 1985. Earthquake Damage Evaluation Data for California. *ATC-13 Report. Applied Technology Council*. Redwood City, California.

[3] Braga, F., Dolce, M. and Liberatore, D. (1982). A Statistical Study on Damaged Buildings and an Ensuing Review of the MSK-76 Scale, Proc. of the 7^{th} European Conference on Earthquake Engineering, Athens, Greece, pp. 431-450.

[4] Calvi, G.M., A displacement-based approach for vulnerability evaluation of classes of buildings, Journal of Earthquake Engineering 3 (1999) 411-438.

[5] Cotton F., Scherbaum F., Bommer J.J., Bungum H. (2006), Criteria for selecting and adjusting ground-motion models for specific target regions: Application to Central Europe and rock sites, Journal of Seismology (2006), 10:137–156

[6] Crowley, H., Silva V. [2012] "Seismic Risk and Loss Assessment," *Course Notes*, European School for Advanced Studies in Reduction of Seismic Risk (ROSE School), University of Pavia, Italy.

[7] Di Pasquale G., Orsini G, Romeo R.W.(2005). New Developments in Seismic Risk Assessment in Italy. Bulletin of Earthquake Engineering (2005) 3:101–128.

[8] Faenza L., Michelini A. (2010), Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap. Geophysical Journal International (2010) 180, 1138–1152.

[9] Federal Emergency Management Agency (FEMA) (1999) Earthquake loss estimation methodology earthquake HAZUS99 Service Release 2 (SR2) technical manual. Washington

[10] Giovinazzi, S., Lagomarsino, S. (2001). "Una metodologia per l'analisi di vulnerabilità sismica del costruito". Atti 10° Convegno Nazionale ANIDIS: L'ingegneria Sismica in Italia, Potenza, Italia

[11] Grunthal, G. (1998). "European Macroseismic Scale 1998. Cahiers du Centre Européen de Géodynamique et de Séismologie", 15: p. 1-97

[12] Hill M.P., Rossetto T (2008), Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe. Bulletin of Earthquake Engineering 6:2, 335–365.

[13] Hill M.P., Rossetto T (2008), Do existing damage scales meet the needs of seismic loss estimation? Proceedings from the 14th World Conference on Earthquake Engineering, 12-17th October 2008, Beijing, China.

[14] Lagomarsino S. and Giovinazzi S. (2006). Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering 4(4), 415-443.

[15] Margottini C., Molin D., Serva L. (1992), Intensity versus ground motion: A new approach using Italian data. Engineering Geology, 33 (1992): 45-58.

[16] Musson R.M.W, Grunthal G., Stucchi M. (2009). The comparison of macroseismic intensity scales, Journal of Seismology (2010), 14:413–428

[17] Nocevski N. (1993). Definition of Empirical and Theoretical Models for Definition of the Vulnerability Level of High-Rises. Doctoral Dissertation, IZIIS, Skopje.

[18] NTC 2008, Norme Tecniche per le Costruzioni, (D.M. 14/01/2008), Gazzetta Ufficiale n.29 01/02/2008

[19] Rossetto T. et al. (2013). Existing empirical vulnerability and fragility functions: Compendium and guide for selection – GEM 2013 Technical Report – X.

[20] Rota M., Penna A., Magenes G. (2010). A methodology for deriving analytical fragility curves for masonry buildings based on stochastic nonlinear analyses. Engineering Structures 32, 1312-1323.

[21] Sabetta F., Goretti A., Lucantoni A.(1998). Empirical Fragility Curves from Damage Surveys and Estimate Strong Ground Motion, Proc. of the 11th European Conference on Earthquake Engineering.

[22] Spillatura A., Fiorini E., Bazzurro P. and Pennucci D. (2014), Harmonized Vulnerability Curves for RC and masonry Structures in the Mediterranean Region" (in preparation)

[23] Trendafiloski G. (2003). GIS-oriented method for elaboration of probabilistic earthquake scenarios. Doctoral disertation, IZIIS-Skopje, January 2003.

[24] Various Authors (2011). Analytical Fragility Functions for Masonry Buildings and Building Aggregates – UPAT methodolgy. Syner-G project Internal Report.

[25] Various Authors [2011], Fragility functions for common Masonry building types in Europe. Syner-G project Deliverable D3.2

[26] Various Authors [2011], Fragility functions for common RC building types in Europe. Syner-G project Deliverable D3.1

[27] Worden C.B., Gerstengerger M.C., Rhoades D.A., Wald D.J. (2012). Probabilistic Relationships between Ground-Motion Parameters and Modified Mercalli Intensity in California. Bulletin of the Seismological Society of America, Vol. 102, No. 1, pp. 204–221, February 2012