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Vulnerability Analysis for Gravity Load Designed RC Buildings in Naples – Italy

MARIA POLESE, GERARDO MARIO VERDERAME, CRISTIANO MARINIELLO, IUNIO IERVOLINO, and GAETANO MANFREDI

Department of Structural Engineering, University of Naples Federico II, Naples, Italy

Damage scenario and risk analyses are helpful tools for the local administrators for mitigation of potential earthquake losses at the urban-regional level. One of the main issues in developing such scenarios is the choice of proper capacity functions expressing the effective seismic supply for the existing building classes and the convolution with demand in the so-called fragility analysis. This article, as a further implementation of a recently developed mechanical based procedure for class scale quantitative risk evaluation, presents the derivation of class representative capacity curves and the relative fragility curves for slight, moderate, extensive, and complete damage states as defined by the well-known HAZUS methodology. Starting from an extensive building survey of Arenella district in Naples, southern Italy, statistics on main model input parameters are obtained for selected building classes of existing and/or pre-code RC buildings. Accordingly, a number of building models is simulated designed and analyzed in order to determine building class capacity. Fragility curves are computed simulating the fraction of "failures" within a capacity spectrum method framework. These capacity and fragility curves have been used in a companion paper by Lang et al. [2008] for the computation of damage scenarios in Arenella.

Keywords Building Inventory; RC Buildings; Simulated Design; Pushover Curves; Fragility Curves

1. Introduction

Regional seismic risk and loss estimation systems need to integrate data and elaborations from different disciplines [Elnashai, 2003]: seismic hazard maps for the site are to be combined with fragility curves to determine expected physical damage; considering the inventory data characterizing the exposed system (building, population) the resulting damage assessment can further be elaborated to estimate economic-social losses. Among these ingredients, seismic fragility curves play a critical role since they represent the probability of attaining different damage states given the ground motion intensity. The computation of fragility curves has been subject of intense research and development over the last decade. A comprehensive categorization of existing methods to fragility curve determination was presented by Rossetto and Elnashai [2003]: the two main approaches are distinguished as empirical and analytical. The former relies on observational data from post-earthquake surveys; in principle, this method is more reliable as long as damage data are available for the region of interest. On the other hand, these

Address correspondence to Maria Polese, Department of Structural Engineering, University of Naples Federico II, Via Claudio 21, 80125 Naples, Italy; E-mail:

curves have the shortcoming of being derived for a specific seismic region and sample, their general application being therefore jeopardized.

Analytical methods rely on structural modelling and analytical evaluation of the aptitude of buildings to be damaged by earthquakes of a given intensity, as well as on consideration of uncertainty modeling for both ground excitation and structural parameters. Although subjective choice of damage representation and questionable reliability of analytic tools determined initial hesitation in the application of these kind of methods, the deepened knowledge of material an structural behavior, improved modeling features for structural components and systems [FIB, 2003], accompanied by the development of more reliable analysis tools and by the enhanced power of new generation of personal computers, make the analytical fragility curves a sustainable and often preferable alternative to empirical ones.

There exist different analytical methods for deriving vulnerability relationships for reinforced concrete (RC) buildings. A first approach adopts simple structural models, such as mechanism-based ones or equivalent SDOF systems, acknowledging the fact that the available data from building inventory are usually very poor [Glaister and Pinho, 2003]. More refined methods (using pushover analyses or dynamic analyses) require a large number of input data for the generic building (geometric, structural, and material properties). For this reason, these methods are generally applied to a single building considered to be representative of an entire population, letting very selected model properties in order to better characterize building response in probabilistic perspective (i.e., Rossetto and Elnashai, 2005).

In Hazus code [FEMA, 1999], which follows a hybrid statistic-mechanical approach, the methodology to estimate damage from an earthquake uses two sets of functions: (1) capacity curves; and (2) fragility curves [Kircher *et al*., 1997]. Capacity curves estimate peak response of buildings for a given level of spectral demand and are analogous to push-over curves. Fragility curves, representing the probability of reaching or exceeding selected damage states, are expressed as lognormal functions given deterministic (median) estimates of spectral response and the expected variability due to capacity curve properties, damage states, and ground shaking. Hazus is probably the more complete framework for the prediction of the effects of scenario earthquakes within urban areas or across large regions; however, its capacity and fragility functions are derived for building typologies that are typical for the U.S. and do not necessarily apply to those of other study areas.

As a partial fulfilment of the research activities planned in the work package 3 of SAFER project (http://www.safrproject.net), which has as a goal the development of fast algorithms for damage scenario simulations and the improvement of existing methods for real-time simulation and prediction of human and infrastructure losses, the research unit of the University of Naples derived capacity and fragility curves for selected building typologies representative of the built environment in Arenella district in Naples, southern Italy, that is one of the test sites for SAFER. The curves, whose derivation is presented in this article, are utilized in a companion paper from [Lang *et al*. 2008] to estimate damage and loss scenarios in Arenella for a selected scenario earthquake.

2. Outline of the Method

The approach utilized herein is a further implementation of a recently developed mechanical based procedure for class scale quantitative risk evaluation [Iervolino *et al*., 2007]. In such a method, the vulnerability of a building class is analyzed starting from push-over analyses performed for virtually all the buildings belonging to such class. In addition to material properties, variation of building dimensions and structural configuration is considered within a class [Iervolino *et al*., 2004]. In this way, it is possible to avoid the choice of a single representative building to catch the capacity and demand variability within the class.

The method consists of a series of subsequent steps: (a) perform building inventory (the more detailed, the less the variation in the results) and determine statistics of the building model input parameters; (b) generate a sample of building models with simulated design process, perform push-over analyses, and determine global capacity parameters, such as nonlinear strength, displacement capacity, and the effective period T of the equivalent SDOF, for each one of them; (c) run Montecarlo analysis extracting random model input parameters, corresponding to generic building within the class, from the relative statistics (c') calculate the capacity by local regression from the capacities of sample buildings (c'') compare capacity with demand, in a capacity spectrum framework, to determine fragility curves for slight, moderate, extensive, and complete damage.

In the next sections, the steps of the procedure that are peculiar to the Arenella application will be described.

3. Building Inventory

The preparation of an inventory of the built environment is usually the most time-consuming and costly step in loss assessment. It could be performed at different levels of detail, strongly depending on the size of the building stock. The most innovative techniques based on image processing, remote sensing, integration of remote sensing and GPS [Tralli, 2000], that are generally appropriate for large regions survey, allow rough categorization of buildings into selected typologies and determination of dimensions and height. However, in densely inhabited areas it is common that single buildings are aggregated into larger blocks that cannot be distinguished if not by sidewalk survey. Moreover, there are other important structural characteristics, such as soft story and irregular infill distribution or, going into more detail, the beams dimensions and typology [Bal *et al*., 2007], as well as material properties, that strongly influence the seismic response and can only be detected by local survey.

3.1. The Arenella District Survey

The Arenella district in Naples, southern Italy, is one of the test sites chosen for application in the SAFER project. With its extension of 5.25 km^2 and population of 72,000 inhabitants, it has one of the highest population densities in Europe. The building stock in this area (approximately 500 aggregates/blocks corresponding to more than 1,500 buildings) is constituted mainly by mid and high-rise RC moment resisting frames built during the 20 years immediately following World War II, before seismic regulations were introduced for the city of Naples (pre-code buildings).

Building survey covered the center-east part of the district, the rest being mainly a green hilly untutored zone. Sidewalk pre-screening allowed to identify single buildings from aggregates (more than 1,400 buildings were identified) and the relative construction typology (RC, masonry M, other). Cartographic and exterior surveys, extended to all the identified RC buildings (more than 850), were complementary in the acquisition of global dimensional and morphologic data, as well as of aspects related to possible deficiencies (irregular infill distribution, soft story etc.). Figure 1 shows a construction age map of the surveyed buildings (information acquired by municipal maps).

FIGURE 1 Construction age of the surveyed buildings — center-east part of Arenella district.

Internal inspection of a limited number of randomly extracted buildings, together with the consultation of a number of architectural drawings, allowed to gather more detailed information, such as stair type, slab way and thickness, resisting element dimensions, structural mesh organization, etc., that have been used to calibrate the simulated design process at the base of the analytical developments of the method (to follow).

3.2. Survey Statistics

The census returns on the studied area available on the website of the Naples' Municipality (www.comune.napoli.it), evidence that more than 55% of the buildings were built between 1945 and 1970, the seismic code-conforming constructions (built after 1981) being less than 2%; more than 85% of the buildings are mainly residential and nearly 70% of the buildings have story number $\geq$ 4. In as regards to building typology (data from pre-screening and cartographic survey), it results that nearly 60% of the buildings are RC frames (more than 850 buildings), whether masonry ones are less tan 20%, the rest being categorized as "other" (non homogeneous structural type made of RC frames infilled with thick masonry blocks, steel constructions, etc.).

A more suitable distribution of the total built area among RC and M buildings could be obtained defining the *elevation area* as the product of building footprint area times the story number; this parameter is more straightforwardly linked to population density and is therefore more significant in loss studies. More than 87% of the elevation area is made of RC pre-code buildings. Referring to the sole latter class, a further sub-classification is introduced distinguishing among RC frame structures with 1 – 3 (RC1), 4 – 6 (RC4), or more than 7 stories (RC7). In particular, more than 80% of the elevation area within these sub-classes (simply called classes in the following) pertains to RC7 class, less than 15% to RC4 and less than 4% to RC1. Story number distribution is shown in Fig. 2a. The great part of the buildings have 8 stories, RC7 class being, in general, the most numerous; one story buildings are mainly very small single-family custodian residences, neglected in further developments. The base plant morphology is categorized in C, L, rectangular (R), S, T, and Other (O) shape. Percent distribution for RC pre-code buildings is shown in Fig. 2b; as it can be seen nearly 70% of the population has rectangular morphology, other main shapes covering less than 20% (L shape) and 10% (C shape), respectively.

Having named L_x and L_y the linear dimensions along maximum-minimum building lengths for rectangular buildings, Figures 3a, 3b, and 3c show L_x-L_y relative frequency diagrams for the RC1, RC4, and RC7 classes, respectively.

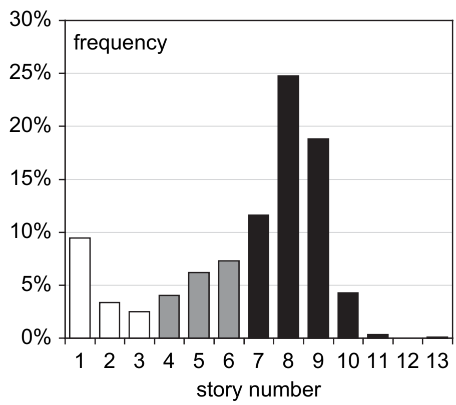

FIGURE 2a Pre-code RC building class: story number percentage. White bars refer to buildings belonging to RC1 class, grey ones to RC4, and black ones to RC7.

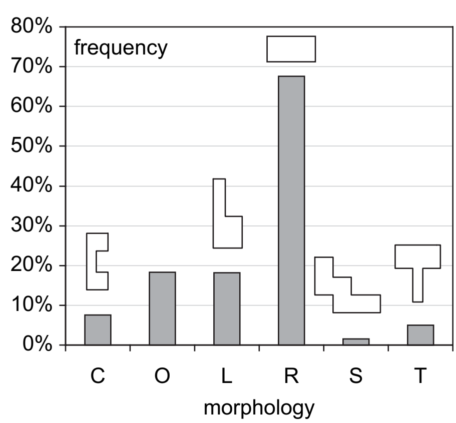

FIGURE 2b Pre-code RC building class: percent distribution of base plant morphology.

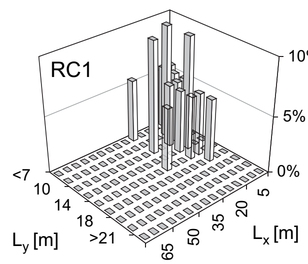

FIGURE 3a Lx-Ly frequency diagram for RC1 class.

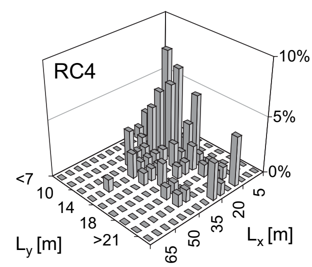

FIGURE 3b Lx-Ly frequency diagram for RC4 class.

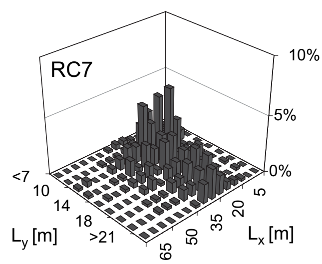

FIGURE 3c Lx-Ly frequency diagram for RC7 class.

4. Building Class Capacity

The simulated design and analysis process covered only rectangular shaped, pre-code RC1, RC4, and RC7 building classes. Simulated design is performed for each single building having global dimensions L_x and L_y and with assigned story number n_z; see Figs. 3a, b, c. Referring to the single L_x-L_y-n_z building a number of geometrical models are defined by the variation of beam-span lengths in x and y directions, a_x, a_y, and inter-story height a_z; see Fig. 4. For each geometric model, the number and location of the structural elements further define a set of structural models. Because the RC buildings in Arenella are mainly moment resisting frames type, the structural system is identified by columns and beams. The latter elements are designed, in terms of cross-section and reinforcement, according to code and design practices related with the construction age. In such a way, the simulated design process allows identifying a set of possible structural models for

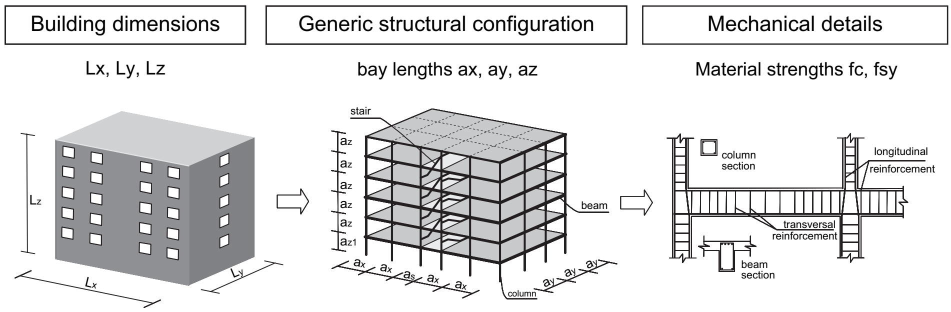

FIGURE 4 Generation of a building model by simulated design [Verderame *et al.*, 2008].

each building that has been only externally defined by its global dimensions [Cosenza *et al.*, 2005; Verderame *et al.*, 2008].

The nonlinear behavior is considered adopting a lumped plasticity model. In particular, the flexural behavior is characterized by the definition of a quadri-linear moment-rotation constitutive law that hits the states of element cracking, yielding, and peak resistance. Yield rotation is evaluated as suggested in Panagiotakos and Fardis [2001], whether the ultimate plastic rotation value is characterized as in ATC [1996].

In order to reproduce a significant sample of building models, effectively representing the existing building stock, the simulated design is applied to a number of buildings defined by L_x-L_y dimensions conveniently chosen from those observed for each class; see Fig. 3. Considering variation of geometric and structural configuration and material properties within each building more than 400 structures are analyzed. Push-over analysis along short direction is performed for each one of them; short direction is generally the weaker one for the Italian gravity load designed buildings [Mariniello, 2007].

Figures 5a, 5b, and 5c show the push-over curves obtained for RC1, RC4, and RC7 classes, respectively; the curves are displayed up to the plastic mechanism formation. Following the criteria suggested in HAZUS to relate component deformation to average inter-story drift ratio Δ_{ds}, the four significant damage thresholds of slight (SD), moderate (MD), extensive (ED), and complete damage (CD) are detected along each push-over curve in terms of roof displacement Δ. According to HAZUS, the selected thresholds, corresponding to the spreading of the plastic mechanism through the building, should be roughly representative of increasing levels of structural damage.

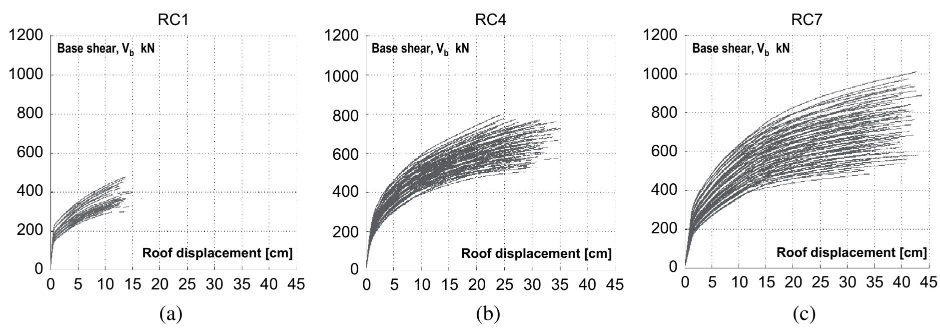

FIGURE 5 Pushover curves of the simulated structures: (a) RC1 class, (b) RC4 class, (c) RC7 class.

Capacity curves are obtained expressing the pushover curves in spectral coordinates. Transforming the capacity curve into bilinear form for each damage threshold, it is possible to estimate the non-linear strength C_s, capacity displacement C_d, and the effective period T of the correspondent SDOF structure.

The seismic capacity of an entire class may be represented by the statistical distributions of C_s, C_d, and T. In fact, as outlined in Sec. 2, distributions of the nonlinear capacity parameters may be obtained via Montecarlo simulation, in which the model parameters are randomly extracted from their distributions. In particular, L_x and L_y ranges are calibrated based on inventory data. Inter-story height is kept constant (a_z 4.5 m for the first level and 3.0 m for upper stories) being its variation negligible within surveyed buildings. In this framework, beam lengths (bay modules along x and y direction) are randomly extracted from uniform distribution, a_x, $a_y \in [4\text{m}, 5\text{m}]$. Concrete and steel strengths f_c and f_{sy} are normally distributed with mean 25 N/mm^2 and 400 N/mm^2 and CoV 25% and 15%, respectively [Verderame *et al.*, 2001a, b].

In every run of the simulation a realization of these factors is extracted. Such realization is assumed to virtually correspond to a building in the class, the SDOF capacity curve of which has to be determined via the proper C_s, C_d, and T. These parameters are computed via linear regression of the values corresponding to the structures "most similar", among those previously analyzed via push-over analysis, to that extracted.

The procedure described allows to develop the fragility curves for each class (to follow), and also to derive the cumulative distributions of C_s, C_d, and T, as given in Fig. 6, which may be useful to compare the results for each class considered.

As it can be observed from Fig. 6, that refers to the complete damage, mid-and high-rise buildings (RC4 and RC7 classes) have similar capacities, rather different with respect to RC1 class. Building belonging to the latter class, in fact, are characterized by a higher nonlinear strength C_s, approximately 2 times larger, and by a lower displacement capacity, approximately 3 times smaller than the other classes. This trend in similar with respect to the effective period. The low variability of capacity parameters for low-rise building class RC1 is to be connected to the relatively small extension of the class in the sample area, as shown in Fig. 3.

5. Fragility Curves Derivation

To evaluate fragility curves for the considered classes of buildings, the same procedure used to compute the unconditional seismic risk in Iervolino *et al.* [2007] was used here. In

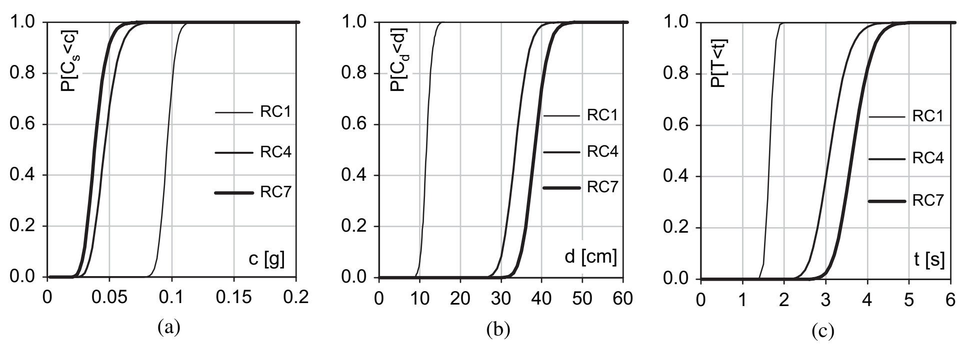

FIGURE 6 Cumulative distribution of capacity parameters at complete damage state for RC1–4–7 classes: (a) nonlinear strength C_s; (b) displacement capacity C_d; and (c) effective period T.

particular, the simulation consists of extracting a vector of the input parameters from the distributions of geometrical features and materials. The SDOF capacity curve corresponding to such vector is then determined as described in the previous section.

The elastic demand is obtained by Eurocode 8 [CEN, 2003] spectral shape for soil type B, Figs. 7a and 7b, that corresponds to NEHRP-site class C (average shear-wave velocity $v_{s,30}$ = 360–760 m/s).

The spectrum is entered with the T value of the capacity curve and the elastic displacement demand S_d is derived. The inelastic demand is evaluated multiplying the elastic displacement demand by a modification factor (C_R) that depends on effective period T and on the spectral reduction factor R [Ruiz-Garcia and Miranda, 2003]. Consequently, nonlinear displacement capacity and demand may be compared in each run checking for failure at each of the four considered damage thresholds. Scaling the elastic spectrum in order to investigate the demand range of interest, and stratifying the results as a function of the elastic displacement, allows to plot the fragility curves.

The curves are approximated with lognormal expressions as suggested in HAZUS. Indicating with S_{dm} the spectral displacement corresponding to the 50% of probability of attaining a given damage state ($P[ds|S_{dm}] = 0.5$), the analytical formulation of the fragility curves is:

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}} \cdot \ln\left(\frac{S_d}{S_{dm}}\right)\right] \tag{5.1}$$

where Φ is the Gauss function and β_{ds} is the parameter related with the slope of the curve. In particular, the fragility curves that are plotted in Figs. 8–10 are obtained considering different sources of uncertainty.

Figures 8a-c show the slight, moderate, extensive and complete damage fragility curves for the RC1, RC4, and RC7 classes, respectively, where the curve variability β_{ds} is only due to the variation of geometric dimensions and material properties within the building class.

In Figs. 9a-c, the limit state threshold variability is also considered assigning proper statistics to yield and ultimate rotation of the elements according to Panagiotakos and Fardis [2001]; as it can be seen the curve slope is significantly higher with respect to the previous case.

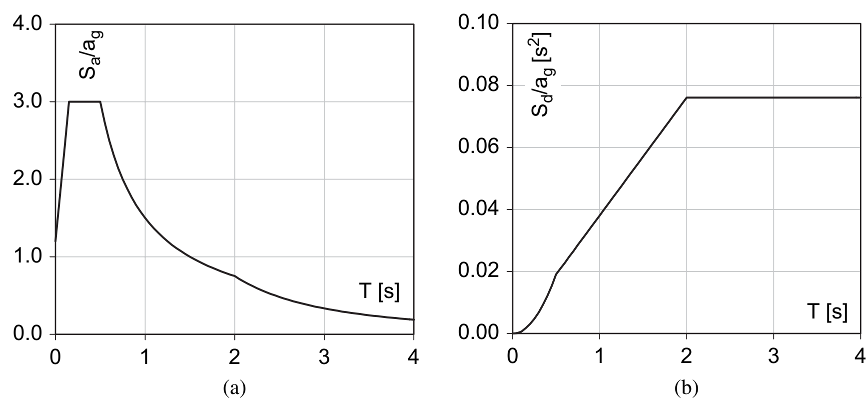

FIGURE 7 Elastic response spectra for Eurocode 8, soil type B, in terms of acceleration (a) and displacement (b) normalized with respect to a_g, the anchoring value [CEN, 2003].

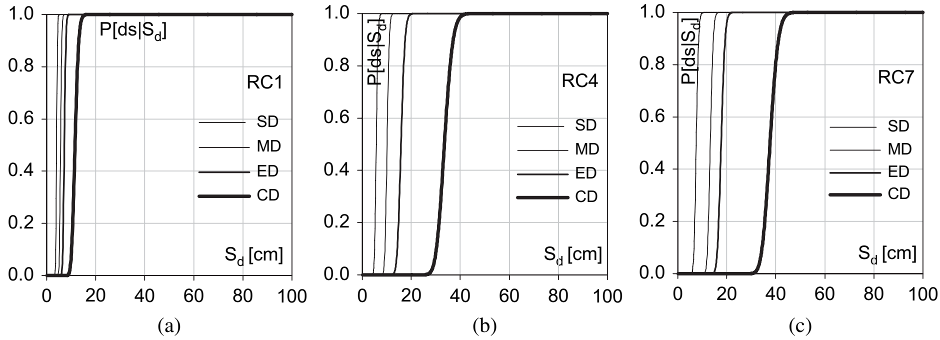

FIGURE 8 Fragility curves accounting for variation of geometric dimensions and material properties: (a) RC1 class, (b) RC4 class, (c) RC7 class.

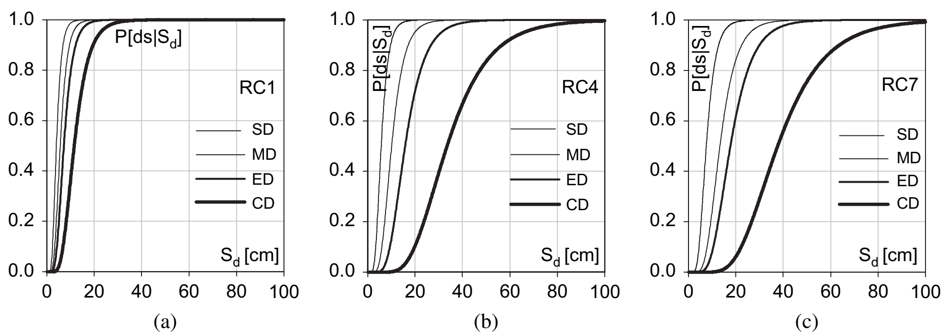

FIGURE 9 Fragility curves accounting for variation of geometric dimensions, material properties and for limit state threshold variability: (a) RC1 class, (b) RC4 class, (c) RC7 class.

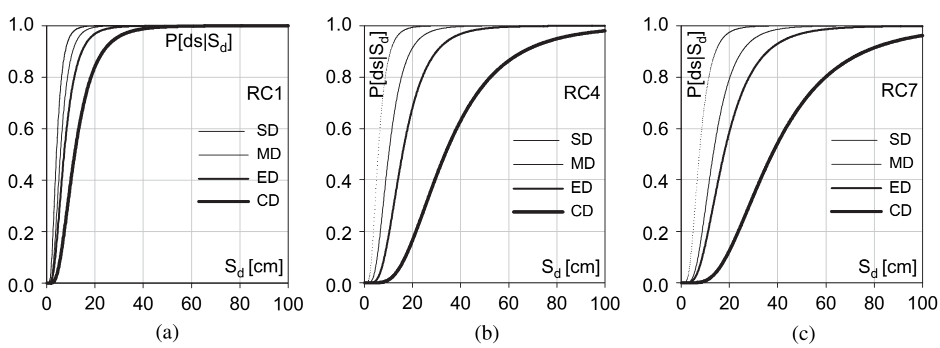

FIGURE 10 Fragility curves accounting for variation of geometric dimensions, material properties, limit state threshold variability and demand uncertainty: (a) RC1 class, (b) RC4 class, (c) RC7 class.

Finally, uncertainties in the seismic demand evaluation are further introduced accounting for the variability of inelastic modification factor C_R; in fact, the conditional distribution of C_R, given {T, R}, may be assumed to be lognormal of parameters provided in Ruiz-Garcia and Miranda [2003]. Figures 10a-c show the resulting fragility curves for all the considered classes and damage thresholds; consistently with the large uncertainty associated to the inelastic demand, the slope of these latter curves is even higher than in Figs. 8 and 9.

As it can be observed, the fragility curves are different and they vary in accordance to the cumulative distributions of capacity parameters. In particular, the RC4 and RC7 curves are comparable for each of the considered damage states. This is due to the fact that capacity parameters C_s and C_d vary in similar ranges, as shown in Fig. 6. Concerning RC1 fragility curves, they are shifted to lower displacement values, as it could be expected from the relatively lower displacement capacity.

6. Conclusions

The study presented in this article summarizes the vulnerability analysis for the case study of the Arenella district in Naples (southern Italy). The building inventory of the surveyed area shows that the population is mainly made of RC moment resisting frame structures. These buildings are of regular shape with variable number of stories, which lead to the definition of three classes. For each of those, fragility curves in terms of elastic spectral displacement are derived via a mechanical approach, which relies on push-over analysis of selected buildings. The analysis considered four damage states, from slight to complete, complying with popular HAZUS classification.

Uncertainties the fragilities account for are those of the surveyed parameters; moreover, variability of the limit-state thresholds and of the inelastic demand are also included. Results show that dispersions of geometrical configuration and material properties have comparatively less influence on the vulnerability for all classes investigated.

Acknowledgments

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References

ATC [1996] "Seismic evaluation and retrofit of concrete buildings," ATC-40 report, Vol. 1, *Applied Technology Council*, Redwood City, California.

Bal, I. E., Crowley, H., Pinho, R., and Gulai, F. G., [2007] "Structural characteristics of Turkish RC building stock in Northern Marmara region for loss assessment applications," *Iuss Press Report*, Pavia, Italy, ISBN: 978–88–6198–003–7.

CEN – Comitée Européen de Normalisation, European Standard EN 1998–1 [2003], *Eurocode 8: Design of structures for earthquake resistance -Part 1: General rules, seismic actions and rules for buildings*, Brussels.

Cosenza, E., Manfredi, G., Polese, M., and Verderame, G. M. [2005] "A multilevel approach to the capacity assessment of rc buildings," *Journal of Earthquake Engineering*, **9**(1), p. 1–22.

Fajfar, P. [1999] "Capacity spectrum method based on inelastic demand spectra," *Earthquake Engineering and Structural Dynamics* **28**, 979–93.

Elnashai, A S. [2003] "Next generation vulnerability functions for RC structures" *Proceeding of the response of Structures to Extreme Loading*, Toronto, Aug. 3–6.

FEMA HAZUS99 [1999], "Earthquake Loss Estimation Methodology: User's Manual," Federal Emergency Management Agency, Washington, D.C.

Fib [2003]. "Seismic assessment and retrofit of reinforced concrete buildings," *Bulletin n. 24*, State of art report prepared by Task Group 7.1.

Kircher, C. A., Nassar, A. A., Kustu, O., and Holmes, W. T. [1997]. "Development of building damage functions for earthquake loss estimation," *Earthquake Spectra*, **13**(4), 663–682.

Glaister, S. and Pinho R. [2003] "Development of a simplified deformation-based method for seismic vulnerability assessment," *Journal of Earthquake Engineering* **7**(1), 107–140.

Iervolino, I., Fabbrocino, G. and Manfredi, G. [2004] "Fragility of standard industrial structures by a response surface based method," *Journal of Earthquake Engineering* **8**:927–46.

Iervolino, I., Manfredi, G., Polese, M., Verderame, G. M., and Fabbrocino, G. [2007] "Seismic risk of RC building classes," *Engineering Structures* **29**, 813–820.

Lang, D., Molina, P. S., and Lindholm, C. [2008] "Towards near real-time damage estimation using a csm-based tool for seismic risk assessment," *Journal of Earthquake Engineering*, **12**(S2), 199–210

Marinello, C. [2007] "Una procedura meccanica nella valutazione della vulnerabilità sismica di edifici in c.a.," Ph.D.Thesis, Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli Federico II. Advisor: G. Manfredi (in Italian).

Panagiotakos, T. and Fardis, M. N. [2001] "Deformation of r.c. members at yielding and ultimate," *ACI Structural Journal* **98**(2), 135–148.

Rossetto, T. and Elnashai, A. S. [2003] "Derivation of vulnerability functions for European-type RC structures based on observational data," *Engineering Structures* **25**, 1241–1263.

Rossetto, T. and Elnashai, A. S. [2005] "A new analytical procedure for the derivation of displacement-based vulnerability curves for populations of RC structures," *Engineering Structures* **27**, 397–409.

Tralli, D. M. [2000] "Assessment of advanced technologies for loss estimation," Special publication MCEER-00-SP02 (on CD-ROM).

Verderame, G. M., Polese, M., Mariniello, C., and Manfredi, G., [2008] "A simulated design procedure for the assessment of seismic capacity of existing RC buildings," *Advances in Engineering Software*, Accepted.

Verderame, G. M., Manfredi, G., and Frunzio G. [2001] "Mechanical properties of concretes adopted in R.C. structures in the age '60" (in Italian), *Proceedings of the 10th National ANIDIS Conference: Seismic Engineering in Italy*, Potenza-Matera.

Verderame, G. M., Stella, A., and Cosenza, E. [2001] "Mechanical properties of reinforcing steel adopted in R.C. structures in the age '60" (in Italian), *Proceedings of the 10th National ANIDIS Conference: Seismic Engineering in Italy*, Potenza-Matera.