Seismic vulnerability: from building evaluation to a typology generalization

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SUMMARY:
Outlining the best strategies for seismic risk mitigation requires that both benefits and costs of retrofitting are known in advance. The assessment of the vulnerability of building typologies is a first step of a more extensive effort, concerning the analysis of the viability of seismic risk mitigation and taking into account retrofitting costs.
The methodology adopted to obtain the seismic vulnerability of some classes of residential buildings existing in mainland Portugal is presented. This methodology is based on a structural analysis of individual buildings belonging to the same typology. An application example is presented to illustrate the methodology.
Fragility curves of "boxed" building typology are also presented and broken down into three height classes: low-rise, medium-rise and high-rise. These curves are based on average capacity spectra derived from several individual buildings belonging to the same typology.

Keywords: building typologies, capacity spectra, fragility curves, seismic damages, seismic vulnerability.

1. INTRODUCTION

Throughout its history, Portugal has suffered the catastrophic effects of several earthquakes that originated significant damages and losses in their buildings and inhabitants. However, seismic activity in mainland Portugal is characterized by low frequency events which may, or may not, have great impact on society. For instance, in the last century, only 1909 and 1969 earthquakes caused some damage in mainland Portuguese building stock. Therefore, statistical studies of vulnerability based on damage surveys are not available for this region.
In this work, a methodology involving the calculation of vulnerability with non-linear analysis techniques was adopted to overcome the lack of information derived from lessons of past earthquakes.
This paper synthesises the adopted methodology to evaluate individual buildings vulnerability and shows how this vulnerability can be generalized to a building typology. The evaluation of the vulnerability of the "boxed" buildings, representative of a typology of Portuguese residential building stock, is also presented as a case study.
It is proposed that the current approach is applied in studies of seismic loss assessment and risk analysis, where vulnerability and fragility curves need to be updated to consider the specific constructive practices of a region.

2. METHODOLOGY

The methodology starts with the study of available information concerning the buildings belonging to the involved typology.
From existing information, the selection of representative buildings is necessary. The diversity of in-plan areas, number of floors, used materials, and other relevant information, is crucial to obtain a successful representation. Where appropriate, the increase of the sampling may be accomplished by

modelling the original buildings changing the number of floors and / or the in-plan area, ensuring that new models will be also representative of the studied typology.

A pushover analysis of all the models according to ATC40 [1996], allows to obtain the correspondent capacity curves. Buildings capacity curves are exhaustively analysed and verified, to find out what are the curves that best characterize the building typology behaviour. A probabilistic analysis of results is performed and the individual fragility curves of the buildings are constructed, according to HAZUS methodology [HAZUS, 2003b]. To obtain the expected performance point, the N2 methodology [Fajfar, 2000] is used, according to Eurocode 8 [EN 1998 – 1: 2004]. From the intersection of the performance point with the building fragility curves, the expected seismic damage is determined and the correspondent repair cost is estimated as a function of the construction cost, according to HAZUS [2003a]. Ensuring that the sample is statistically representative, the average of capacity curves values provides the support to initiate the vulnerability evaluation of a building typology.

3. APPLICATION EXAMPLE

3.1. Initial remarks

In the universe of buildings belonging to a given building typology, some buildings in Lisbon were selected to be evaluated. Given the example of a "box" building typology, medium-rise (from three to five floors buildings), three buildings with similar in-plan areas and behaviour were chosen, but with different composition and organization of the construction elements. In order to obtain a larger number of results, the three original buildings were also simulated with one extra floor and one less floor. Other variations in future analyses should include changes in the in-plan areas.

The individual analysis for one building is presented next, followed by the generalization to the building typology, using the obtained values from the three chosen buildings.

3.2. Building characterization

The selected building is located at the *Bairro de Alvalade*, in Lisbon. It was constructed in 1949 and belongs to a series of a dozen of similar buildings with residential use. The building has a total area of 320 m^2, and has four floors (Fig. 3.1 and 3.2).

From the constructive point of view, the building is composed by reinforced concrete columns and beams in the main facades and gables in reinforced concrete walls with 0,20m of thickness. The exterior walls are constituted by two panels of perforated bricks, including a small cavity. The walls of the stairwell and the principal partition wall are also in perforated bricks. The remaining interior walls are of perforated bricks on the ground and first floor and of solid brick on the 2nd and 3rd floors. The pavements are of reinforced concrete slabs, with 0,10m thick, reinforced with a single steel layer in both directions.
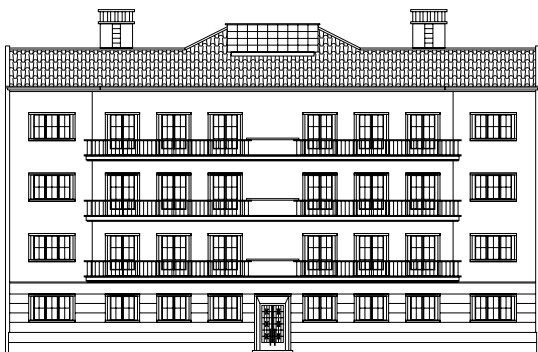

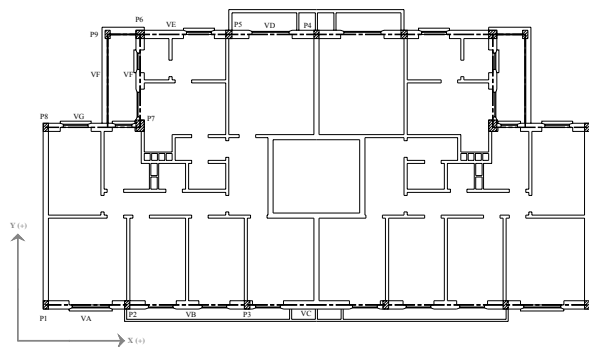**Figure 3.1.** Main façade

Figure 3.2. Location of walls and exterior concrete structure

3.3. Building analysis

The selected building was introduced in the program 3Muri, considering both systems types: frames for reinforced concrete elements and macro-elements for the brick walls (Fig. 3.3). A pushover analysis was performed in the two main directions of the original building, according to ATC40 [1996], in the positive and negative directions. The uncertainty associated with the structural parameters was considered by carrying out various models of the building, with different material properties.
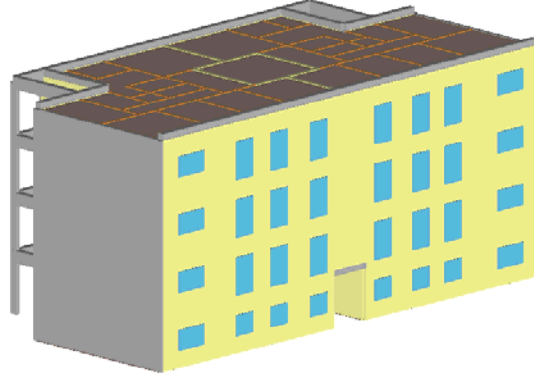
Figure 3.3. Image of the selected building model

The capacity curves obtained from the pushover analysis (a curve relating base shear versus roof displacement) were converted in the ADRS format (a curve relating spectral acceleration with spectral displacement, also called *capacity spectrum*), for subsequent comparison with the demand spectra of the seismic action. The conversion to the ADRS format was performed according to ATC40 [1996], using equations 3.1 and 3.2.

$$S_a = \frac{V/W}{\alpha_1}, \text{ and } \alpha_1 = \frac{\left[\sum_{i=1}^{N}(w_i\phi_{i1})/g\right]^2}{\left[\sum_{i=1}^{N}w_i/g\right]\left[\sum_{i=1}^{N}(w_i\phi_{i1}^2)/g\right]} \tag{3.1}$$

$$S_d = \frac{\Delta_{roof}}{PF_1\phi_{roof,1}}, \text{ and } PF_1 = \left[\frac{\sum_{i=1}^{N}(w_i\phi_{i1})/g}{\sum_{i=1}^{N}(w_i\phi_{i1}^2)/g}\right] \tag{3.2}$$

where

PF_1 is the modal participation factor for the first natural mode;

α_1 represents the modal mass coefficient for the first natural mode;

w_i/g is the mass associated to level i;

ϕ_{i1} stands for the amplitude of mode 1 at level i;

N is the level which is the uppermost in the main portion of the structure (number of floors);
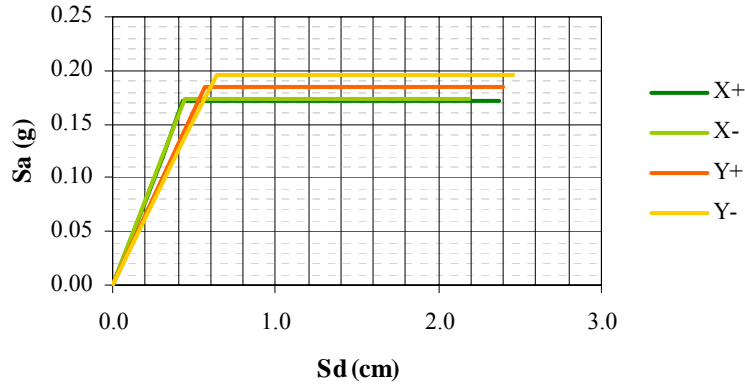V corresponds to the base shear;
W is the building dead weight plus quasi-permanent live loads;

Δ_{roof} is the roof displacement;

S_a is the symbol of the spectral acceleration;

S_d symbolizes the spectral displacement.

The final capacity spectra of the selected building are presented in Fig. 3.4. This figure shows the median value obtained for each direction, considering the variability of the material properties.

Figure 3.4. Median capacity spectra (ADRS format)

Following a conservative approach, the capacity spectra that was selected to be representative of the building behaviour corresponds to the highest damage value. The procedure adopted is presented next and takes into account the seismic action, the probability of exceedance of each damage state and the correspondent repair cost.

3.4. Construction of fragility curves

Building fragility curves give information on a conditional probability distribution of damage, i.e., the probability of the building to match, or to exceed, a certain state of damage, given a value of the spectral acceleration or spectral displacement. In this case, the damage distribution depends on the spectral displacement, and according to HAZUS [2003], is described as a lognormal distribution function:

$$P[DS > ds \mid S_d] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \tag{3.3}$$

where

$\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds;

β_{ds} represents the standard deviation of the natural logarithm of spectral displacement for damage state, ds;

Φ is the symbol of the standard normal cumulative distribution function.

Five damage states were considered:
1. no damage (D_0);
2. light damage (D_1);
3. moderate damage (D_2);
4. extensive damage (D_3);
5. total damage or collapse (D_4).

According to [RISK-UE, 2003 and Barbat et al, 2008], the median values of the spectral displacement associated with the limit of each damage state and the correspondent value of standard deviation are dependent on the elastic displacement and on the ultimate displacement of the building. These parameters are presented in Table 3.1.

Table 3.1. Characterizing parameters of fragility curves [RISK-UE, 2003 and Barbat et al, 2008]

Damage state	D_1	D_2	D_3	D_4
$\overline{S}_{d,ds}$	$0.70 Sd_y$	Sd_y	$Sd_y + 0.25(Sd_u - Sd_y)$	Sd_u
β_{ds}	$0.25 + 0.07\ln(\mu_u)$	$0.20 + 0.18\ln(\mu_u)$	$0.10 + 0.40\ln(\mu_u)$	$0.15 + 0.50\ln(\mu_u)$

Sd_y - yield spectral displacement; Sd_u - ultimate spectral displacement; μ_u - ultimate ductility
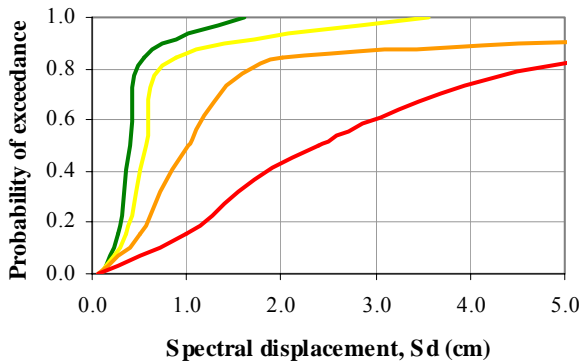
The final fragility curves for the selected building are presented in Fig. 3.5 to Fig. 3.8; the subjacent parameters are presented in Table 3.2.
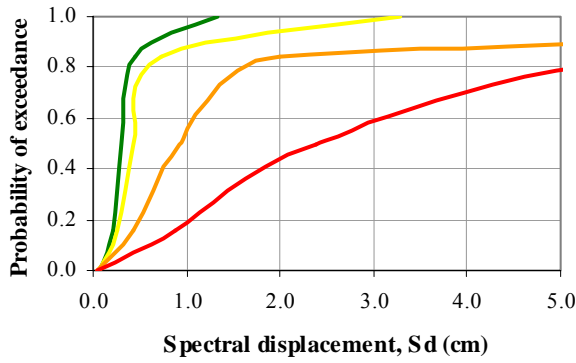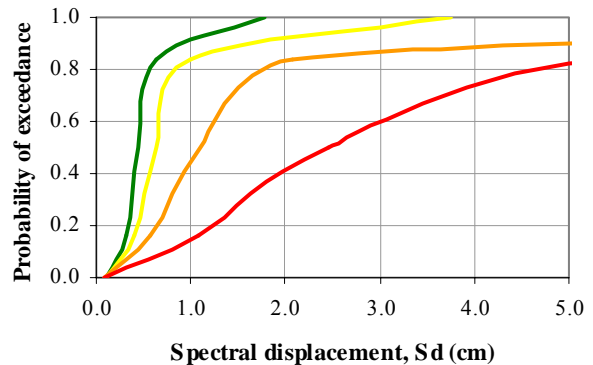

Figure 3.5. Fragility curves of the selected building for X+ direction
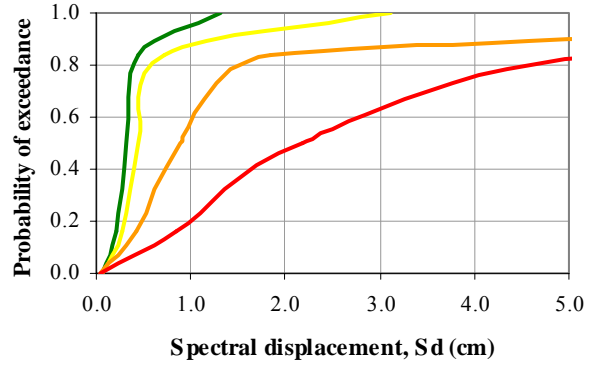
Figure 3.6. Fragility curves of the selected building for X- direction

Figure 3.7. Fragility curves of the selected building for Y+ direction

Figure 3.8. Fragility curves of the selected building for Y- direction

Legend of Figures 3.5 to 3.8:

Light damage

Moderate damage

Extensive damage

Complete damage or collapse

Table 3.2. Parameters of fragility curves for the selected building

Direction	Sd_1	$\beta\,ds_1$	Sd_2	$\beta\,ds_2$	Sd_3	$\beta\,ds_3$	Sd_4	$\beta\,ds_4$
X+	0.30	0.37	0.44	0.51	0.92	0.78	2.38	1.00
X-	0.31	0.36	0.45	0.49	0.88	0.74	2.18	0.94
Y+	0.39	0.35	0.56	0.46	1.02	0.68	2.40	0.87
Y-	0.45	0.34	0.64	0.44	1.09	0.64	2.46	0.82

3.5. The performance point

The performance point of a building represents the maximum response expected for that building, suffering a given ground motion. This point is calculated by the N2 method [Fajfar, 2000]. The procedure depends on the value of the equivalent period of the building (T^*), according to expressions 3.4 or 3.5:

$$\text{If } T^* \geq T_C \; ; \; \mu = R_\mu \; ; \; S_d = S_{de}(T^*) \tag{3.4}$$

$$\text{If } T^* < T_C \; ; \; \mu = (R_\mu - 1)\frac{T_C}{T^*} + 1 \; ; \; S_d = \mu D_y^* = \frac{S_{de}}{R_\mu}\left(1 + (R_\mu - 1)\frac{T_C}{T^*}\right) \tag{3.5}$$

where $R_\mu = \dfrac{S_{ae}(T^*)}{S_{ay}}$ and $S_{ay} = \dfrac{F_y^*}{m^*}$; R_μ is a reduction factor which take place due to the ductility of the structure.

These expressions were applied to obtain the performance point of the selected building. Considering the seismic action type 1 of the Portuguese National Annex of EC8 [NP EN 1998 – 1: 2010], acting in a building constructed on a type B terrain, and the values shown in Table 3.3 were obtained.

Table 3.3. Abscissa of the performance point evaluated for the selected building

Direction	Sd (cm)
X+	1.90
X-	1.89
Y+	2.05
Y-	2.11

The abscissa of the performance point corresponds to the effect of seismic action, measured in terms of spectral displacement. This value conditions the cumulative probability distributions that model building fragility. Fragility curves allow the evaluation of the probability to exceed the threshold of a given damage state, conditioned by a level of seismic ground motion. For the selected building, given the values presented in Table 3.3 for the performance point, and considering the fragility curves presented in Fig. 3.5 to Fig. 3.8, the obtained values for the probability of exceedance of each damage state are shown in Table 3.4.

Table 3.4. Probability of selected building exceed each damage state (%)

Direction	Damage state				
	Sd_4	Sd_3	Sd_2	Sd_1	Sd_0
X+	43	41	10	6	0
X-	45	39	9	7	0
Y+	44	40	9	7	0
Y-	44	40	8	8	0

3.6. Estimation of the repair cost

The value of the repair cost can be estimated as a function of the expected seismic damage through the application of expression 3.6 [HAZUS, 2003a]:

$$C_{RD} = (0 \times P_{D0} + 0.02 \times P_{D1} + 0.10 \times P_{D2} + 0.50 \times P_{D3} + 1.00 \times P_{D4}) \times C_T \qquad (3.6)$$

where
C_{RD} is the repair cost of the seismic damage (€/m^2);
C_T represents the construction cost (€/m^2);
P_{D0}, P_{D1}, P_{D2}, P_{D3}, P_{D4}, are the probabilities of exceedance of the thresholds of the damage states "no damage", "light damage", "moderate damage", "extensive damage", "total damage or collapse", respectively.

The estimated repair cost of the seismic damage for the selected building, direction X+, may be calculated by the following expression:

$$C_{RD} = (0 \times 0 + 0.02 \times 0.06 + 0.10 \times 0.10 + 0.50 \times 0.41 + 1.00 \times 0.43) \times C_T = 0.65 C_T$$

Similarly, the repair costs are estimated for all directions (Table 3.5):

Table 3.5. Estimated repair costs for all directions of the selected building

Direction	Sd (cm)
X+	0.65 C_T
X-	0.66 C_T
Y+	0.65 C_T
Y-	0.65 C_T

Although the selected building presents similar values for repair cost of seismic damage, it can be concluded that direction X- show a highest value for seismic damage. So, the previous values obtained for direction X-, will represent, from now on, the characteristic values of the selected building.

## 4. GENERALIZATION TO THE BUILDING TYPOLOGY

After the analysis of three different buildings belonging to the same typology, it was found that they slightly differ from each other. Thus, and in order to increase the sample values, the same model of buildings has been constructed, increasing and decreasing one floor, always maintaining the variation of material properties. The expected values for the building typology are obtained from the average of the resultant values.
In this example, for "boxed" buildings or "plate" buildings – medium rise (three, four and five floors), the characteristic capacity spectrum is given by the average of individual capacity spectra (Fig. 4.1).
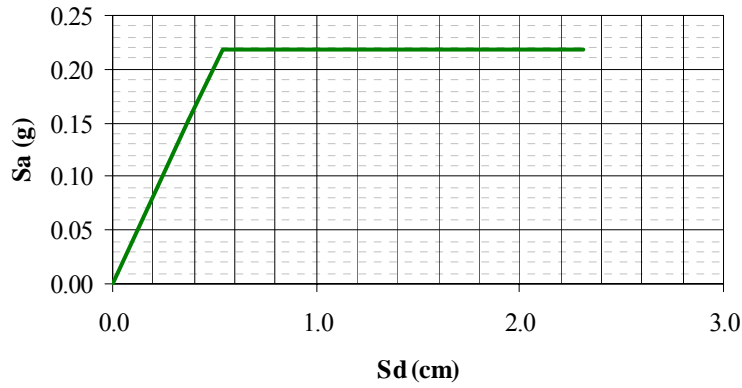
**Figure 4.1.** Average capacity spectrum for "boxed" buildings – medium rise

The characteristic fragility curves of "boxed" buildings, medium-rise, were obtained by using the procedures described in 3.2 and presented in Fig. 4.2 and Table 4.1. Similarly, the characteristics fragility curves for "boxed" buildings, small-rise and high-rise, were estimated (Fig. 4.3 and Fig. 4.4; Table 4.2).
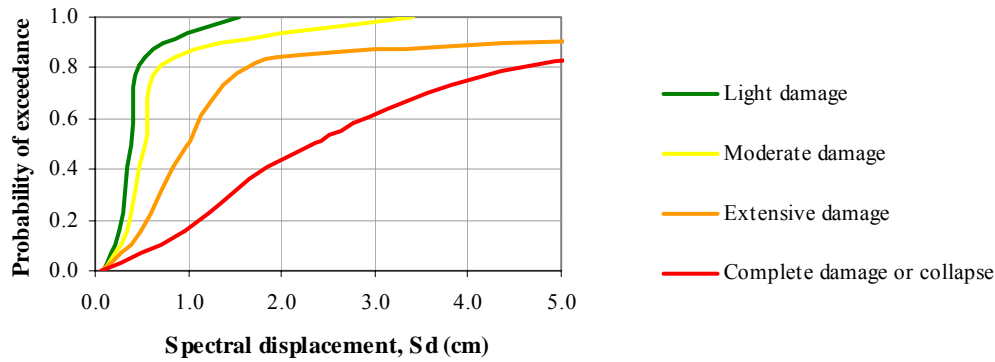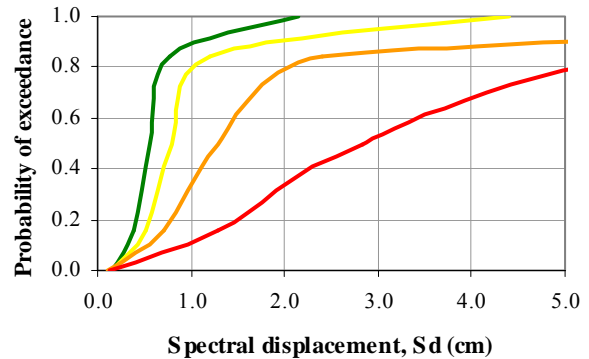

Figure 4.2. Fragility curves for "boxed" buildings – medium-rise

Table 4.1. Characterizing parameters of fragility curves for "boxed" buildings – medium rise

Sd_1	$\beta\, ds_1$	Sd_2	$\beta\, ds_2$	Sd_3	$\beta\, ds_3$	Sd_4	$\beta\, ds_4$
0.38	0.35	0.54	0.46	0.98	0.68	2.31	0.88
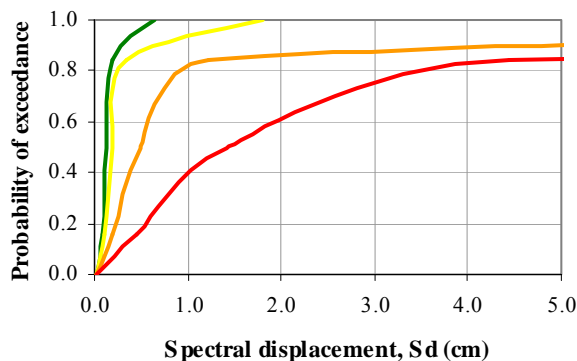
Figure 4.3. Fragility curves for "boxed" buildings small-rise

Figure 4.4. Fragility curves for "boxed" buildings high-rise

Table 4.2. Characterizing parameters of fragility curves for "boxed" buildings – small-rise and high-rise

	Sd_1	$\beta \, ds_1$	Sd_2	$\beta \, ds_2$	Sd_3	$\beta \, ds_3$	Sd_4	$\beta \, ds_4$
Small-rise "boxed" buildings	0.13	0.39	0.19	0.56	0.50	0.90	1.41	1.15
High-rise "boxed" buildings	0.55	0.34	0.79	0.43	1.30	0.61	2.83	0.79

5. CONCLUSIONS

In this paper, a methodology to evaluate the seismic vulnerability of residential buildings was presented.

The methodology is based in a structural analysis approach that starts to analyse the individual buildings belonging to a building typology and later generalizes the results to be representative of that typology.

The study of individual buildings is based on a pushover analysis to obtain capacity spectra [ATC40, 1996], whereas fragility curves were evaluated according to HAZUS [2003b].

An application example was presented and discussed in detail, aiming at characterizing seismic vulnerability of "boxed" buildings, representative of the Portuguese residential building stock, divided by height classes (small, medium and high rise).

The proposed procedure is a step forward to characterize the seismic vulnerability of existing buildings in different regions, that have specific constructive practices, and to obtain fundamental information to be used in seismic loss simulators and in seismic risk studies.

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