11º CONGRESSO NACIONAL DE SISMOLOGIA E ENGENHARIA SÍSMICA

UPDATING FRAGILITY CURVES FOR PORTUGUESE PRE-SEISMIC CODE REINFORCED CONCRETE BUILDINGS

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ABSTRACT

This paper is part of a broader study under development at LNEC with the main aim of defining general policies for the cost-effective seismic retrofitting of the existing Portuguese building stock.
The paper will summarise the methodology implemented for determining accurate capacity and fragility curves of existing pre-seismic design code reinforced concrete (RC) buildings when subjected to seismic action. The methodology involved the definition of probabilistic models of relevant input variables (geometry and materials), performing advanced numerical models of RC buildings under seismic action, setting of appropriate limit states and finally analysis of the results in order to derive the updated curves for Portuguese building stock.
This paper will also present a comparison between curves obtained from the current study and the corresponding curves currently being used in LNEC's seismic risk assessment platform (LNECloss).

KEYWORDS: Fragility Curves, Reinforced Concrete Buildings, Pre-Seismic Code

1. INTRODUCTION

Portugal experienced a very large earthquake in 1755 which affected an area approximately equal to 800 000 km2 and caused almost 100 000 fatalities. The earthquake of 1755 is probably the greatest seismic disaster to have struck western Europe [1].

In Portugal, almost 70% of the existing building stock was not designed with respect to earthquakes and is therefore potentially vulnerable to this type of hazard.

Despite the great advances that have been made in the last decades in the areas of probabilistic seismic hazard assessment (e.g. [2]; [3]), evaluation of building seismic vulnerability [4] and collection of information regarding the elements exposed to the hazards (e.g. [5]), an increase in the trend of earthquake losses is still observed [6]; [7]; [8].

Seismic structural vulnerability can be defined as the likelihood of a certain loss being attained due to the effects of an earthquake on a structure. Consequently, the vulnerability of the exposed elements to seismic events plays a critical role on the value of expected losses. A simple comparison between the consequences of similar earthquakes that occurred in different areas of the world reveals the critical importance of structural vulnerability.

The recognition of the importance in understanding structural vulnerability led to a rapid rise in demand for accurate and flexible methodologies for its evaluation [4]. A fundamental step in seismic vulnerability analyses of structures is the definition of capacity and fragility curves. However, most often these curves are defined using theoretical models calibrated against a limited set of empirical and/or numerical results and are heavily dependent on expert opinion. The use of some of these simplified models facilitates the work flow required for performing seismic risk analyses but often involves substantial uncertainties which can significantly limit the use of the results obtained. The present paper aims to reduce the level of uncertainties associated with seismic structural vulnerability analysis of pre-seismic code RC buildings in Portugal.

2. BACKGROUND

2.1. LNECloss Risk Assessment Platform

2.1.1. *Building damage module*

LNECloss is a seismic scenario risk assessment platform, integrated on a Geographic Information System (GIS), which comprises modules dealing with bedrock input, local soil effects, vulnerability and fragility analysis, human and economic losses.

Building damage module is well described in [9], from where we extracted the following paragraphs.

LNECloss uses the capacity spectrum [10] and the HAZUS loss estimation methodology [10] to evaluate the peak response for each type of building, and determine the correspondent seismic performance point. The evaluation of peak response, for each type of building, relies on the intersection of its capacity curve with the seismic spectral demand at the site. The initial elastic response spectrum is reduced to the demand spectra, to take into account the structural dissipation capacity when exposed to high intensity seismic motions. The procedure is illustrated in Fig. 1.

An innovative robust technique was introduced in LNECloss that considers an equivalent non-linear stochastic iterative procedure to estimate sequential building response, with increasing effective damping, reflecting structure degradation during its cyclic response.

While in HAZUS the modifications of spectral demand are represented by reduction factors, in LNECloss those modifications were performed through an iterative equivalent nonlinear stochastic methodology. Progressive building responses are obtained, until the convergence with the median capacity curve is achieved.

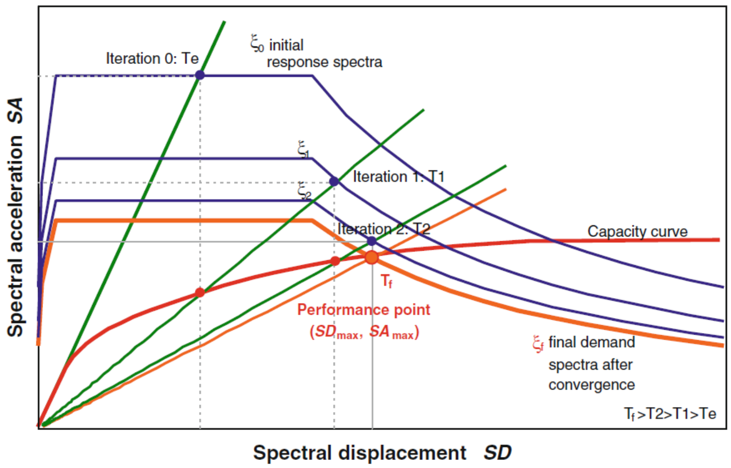

Fig. 1 - Iterative methodology to obtain the performance point in the capacity spectrum method [11]

The performance point, obtained this way, corresponds to the absolute maximum value of the dynamic response of a structure idealized by a single degree of freedom system. The definition of capacity curves follows the FEMA & NIBS [11] methodology, which consists of simple rules in a spectral acceleration (SA) vs spectral displacement (SD) domain (see Fig. 2).

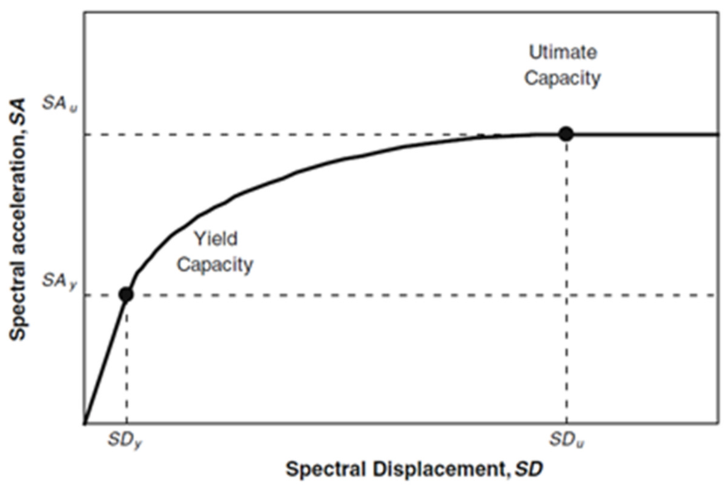

Fig. 2 – Example of a building capacity curve [9]

Those rules use parameters related to the design of structures allowing the definition of capacity curves by two control points, yield capacity (SDy, SAy) and ultimate capacity (SDu, SAu), expressed by

$$SA_y = C_s \cdot \gamma / \alpha_1 \qquad SD_y = SA_y \cdot T_e^2 / (2 \cdot \pi)^2$$
$$SA_u = \lambda \cdot SA_y \qquad SD_u = \lambda \cdot \mu \cdot SD_y \tag{1}$$

where,
Cs is the design strength coefficient (fraction of building weight);
Te the elastic fundamental-mode period of buildings;
α1 is the fraction of building weight effective in push-over mode;
γ is an over strength factor relating yield strength to design strength;
λ is the over strength factor relating ultimate strength to yield strength;
μ is the ductility factor relating ultimate displacement to λ times the yield displacement.

The abscissa of the performance point conditions the cumulative probability distributions that model the fragility of buildings. Fragility curves allow the evaluation of the probability of exceedance of the threshold of a given damage state, conditioned by a level of seismic ground motion. Four damage states are considered, specific for each typology:

- Slight damage;
- Moderate damage;
- Extensive damage;
- Complete Damage.

The threshold of those damage states are established in terms of "equivalent" global drift values, SD , for each typology, and fragility curves are defined by a lognormal distribution function conditional on the maximum response of each building, referred as SDmax:

$$P(D \geq d \mid SD_{\max}) = \Phi\left(\frac{1}{\beta} \cdot \ln\left(\frac{SD_{\max}}{SD_d}\right)\right) \quad (1)$$

where ϕ is the standard normal cumulative distribution function and β is the standard deviation of the natural logarithm of spectral displacement of damage state *d*.

2.1.2. *Updating LNECloss*

LNECloss platform can be used to perform seismic risk studies of several typologies of buildings. However, results are still strongly dependent on expert opinion (used primarily to fit to the Portuguese building stock the HAZUS default values of the parameters needed to define capacity curves and fragility curves).
Vulnerability classes in LNECloss are categorised by the typology of buildings and the period that they were built (Fig.3).

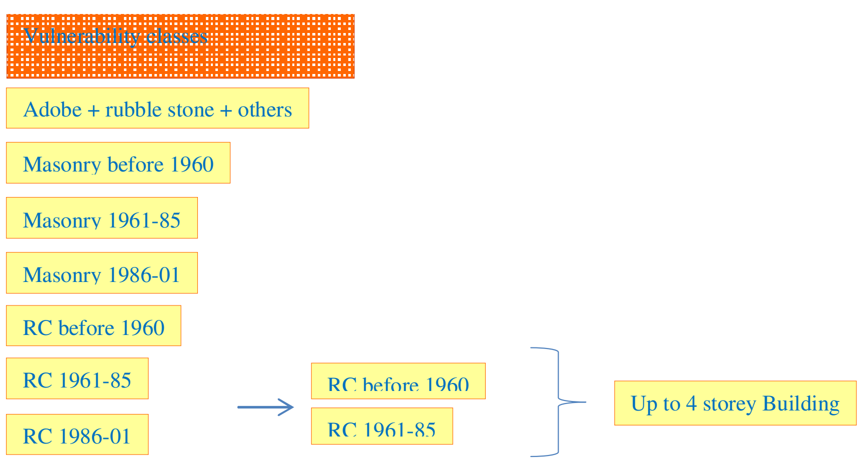

Fig. 3 - Vulnerability Classes in LNECloss risk platform shows in first column; On second and third columns: typologies considered in the current study

Reinforced concrete construction accounts for approximately 50% of the Portuguese building stock and host 60% of the national population. Within this building class, at the time of the 2011 Census Survey [12], 49% of the buildings had not been designed according to the most recent seismic code [13], which represents approximately 3.1 million habitants living in structures that might not be capable of withstanding the effects on an eventual earthquake.
Also according to Census 2011 [12], 97% of the buildings in Portugal are 1 to 4 storeys high.

Considering the above information and taking into account that the influence of numerical uncertainties tend to increase with the height of a building, it was decided to update LNECloss with more accurate input data starting from the pre-seismic code RC buildings of up to 4 storeys.

3. METHODOLOGY

In this study, a methodology was established based on detailed numerical studies of the seismic behaviour of pre-seismic code RC buildings.
In the first step of the methodology, algorithms automatically generated the geometry and the finite element mesh as well as the mechanical properties of three-dimensional RC buildings. For the same building typology (1 to 4 storeys), the characteristics of the structural materials and geometrical properties considered were determined based on the Latin Hypercube Sampling (LHS) method applied to probabilistic models that best fit representative samples of the existing building stock. In total, 200 models were generated for each building typology.
Afterwards, nonlinear static (adaptive) analyses were used to simulate the seismic behaviour of the buildings, before and after being retrofitted.
From the thus obtained capacity curves it was possible to determine fragility curves for the four damage states considered.
The abovementioned methodology is detailed in the foregoing sections.

3.1. Numerical Modeling

Numerical analyses were performed [14] using the SeismoStruct FEA software. The finite elements used to simulate beams and columns were linear force-based elements. Slabs were modelled approximately as rigid diaphragms. The constitutive model used for the steel reinforcement was the Menegotto-Pinto model whereas for the concrete the Mander nonlinear model was considered. The seismic action was applied using an adaptive static pushover analysis, meaning that the load pattern shape could be modified as structural damage progresses.
The values of the most relevant geometrical and mechanical properties of the buildings were sampled from Normal distributions whose parameters are shown in Table 1. For example, the length of the beam spans in each direction (LX and LY) was considered to be a random input variable with mean value equal to 4,4 m, a CV of 16%, a minimum value of 2,5 m and a maximum value of 6,5 m.

Table 1 – Distributions established for the different properties of buildings [14]

Variáveis	Média	CV (%)	A	B
G (kN/m^2)	8	12.5	6	10
N° pisos	1/2/3/4	28/42/15/15	-	-
H_1	3.2	10	2.5	5
H_n	2.8	6	2.5	4
$L_{X/Y}$ (m)	4.4	16	2.5	6.5
h_{laje} (m)	0.23	24	0.1	0.35
f_{cm} (MPa)	23.8	49	5.0	80.0
f_{yk} (MPa)	235/400/500	25/50/25	-	-
ρ_l (%)	1	40	0.3	3.5

Using the above setup, 200 buildings were randomly generated for typology (1 to 4 storeys), in two directions (X, Y) that coincided with the principal axes of the buildings. Examples of the obtained capacity curves are illustrated in Figure 4.

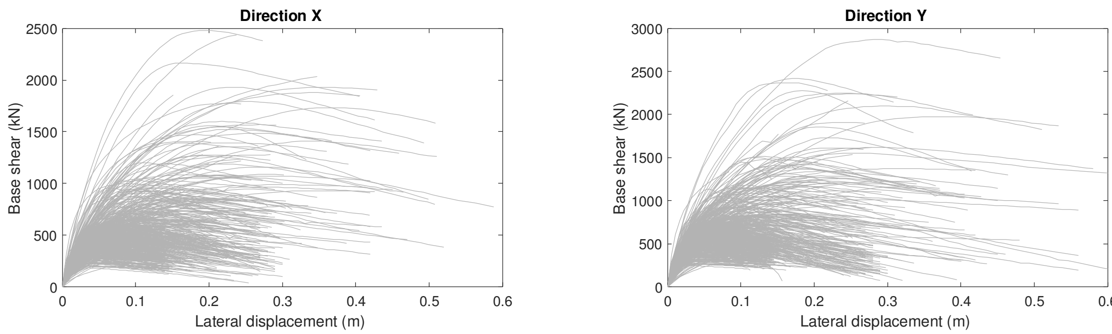

Fig. 4 – Capacity curves of 200 buildings in X and Y direction.

3.2. Limit states definition

Based on the results of the advanced numerical models of representative pre-seismic code Portuguese RC buildings under seismic action, appropriate limit states were defined.

It is noted that the possible options for the limit state criterion can vary significantly and a recognized common approach regarding which criteria should be employed for the development of fragility functions does not seem to exist [15].

In this study, maximum global drifts (e.g.[16]; [15]) are considered for the limit states criterion.

Four different damage states have been defined based on the following:

Slight damage: Drift corresponding to 50% of the maximum base shear capacity;

Moderate damage: Drift corresponding to 75% of the maximum base shear capacity;

Extensive damage: Drift corresponding to the maximum base shear capacity;

Collapse: Drift corresponding to 80% of the ultimate drift.

3.3. Fragility curves

Updated fragility curves were determined using Eq. (1). Numerical and modelling uncertainties were accounted via the β parameter (the standard deviation of the natural logarithm of spectral displacement of damage state d).

The variability due to the input random variables of the buildings was determined by the standard deviation of each one of the four different damage states among the 200 capacity curves of each building typology.

The variability due to the uncertainty in the definition of each one of the four different damage states was determined from HAZUS [17] and considered equal to 0,40 for all building typologies.

The variability due to the seismic action definition (e.g. seismic spectrum) was accounted for in the stochastic models of initiation and propagation of the seismic event include in LNECloss [18].

The combined effect of the former two sources of uncertainty was determined based on a SRSS method. The latter was included directly in the calculation of the seismic spectra.

4. RESULTS

Parameter values necessary to compute mean capacity curves and fragility curves from original LNECloss are given in Table 2 and for the updated LNECloss in Table 3. The values of the parameters Ay, Dy, Au and Du for the updated LNECloss were determined based on least-squares regression analyses for each set of 200 curves for a given building typology.

Table 2 – Original LNECloss input values for determining capacity and fragility curves

Typology	A_y (g)	D_y (cm)	A_u (g)	D_u (cm)	$\overline{SD}$ Slight (cm)	$\overline{SD}$ Moderate (cm)	$\overline{SD}$ Extensive (cm)	$\overline{SD}$ Complete (cm)	β
1 storey	0,122	0,12	0,27	1,36	0,96	2,40	3,84	8,88	0,92
2 storey	0,096	0,27	0,22	2,99	1,73	4,32	7,10	16,61	
3storey	0,083	0,38	0,19	4,26	2,30	5,76	9,79	23,18	
4 storey	0,070	0,57	0,16	5,13	2,69	6,24	11,90	28,61	

Table 3 - Updated LNECloss input values for determining capacity and fragility curves

Typology	A_y (g)	D_y (cm)	A_u (g)	D_u (cm)	$\overline{SD}$ Slight (cm)	$\overline{SD}$ Moderate (cm)	$\overline{SD}$ Extensive (cm)	$\overline{SD}$ Complete (cm)	β
1 storey	0,041	0,40	0,26	9,00	1,17	2,16	5,18	16,89	0,33
2 storey	0,026	0,50	0,19	12,00	1,65	3,15	6,93	15,06	
3storey	0,029	0,85	0,18	16,50	2,41	4,60	10,17	17,47	
4 storey	0,031	1,60	0,17	20,00	3,36	6,36	14,13	21,92	

Figure.5 illustrates the updated fragility curves for 1 storey buildings using Eq. (2) and the curves generated using the 200 capacity curves obtained from the numerical analyses. It can be seen that the lognormal theoretical distribution fits quite well the "real" distribution function.

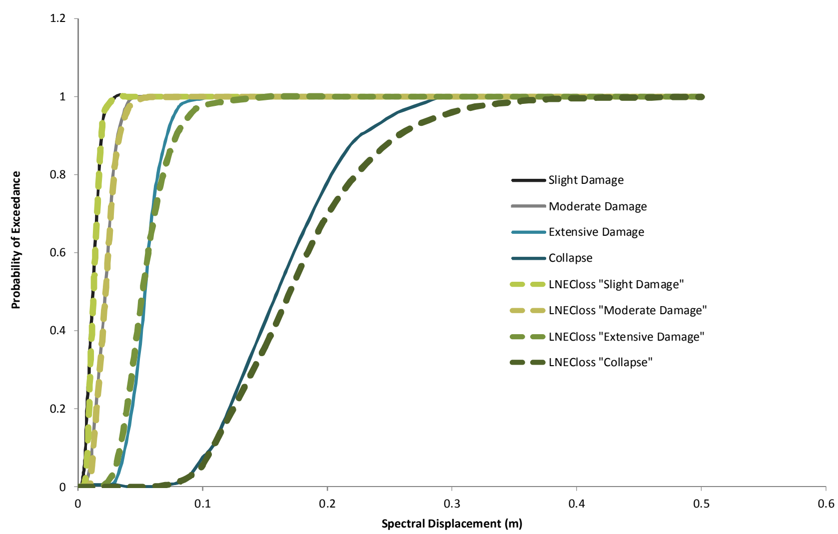

Fig. 5 - Fragility curves for 1 storey buildings using Eq. (2) and Numerical Model

Figures 6 to 9 illustrate the original and updated fragility curves for 1 to 4 storey buildings.
Analyzing the figures below it is possible to compare the original LNECloss curves with the updated ones.

A big gap in curves is observed between the original and updated LNECloss curves. For all damage limit states (i.e. slight up to collapse), the original curves always start returning higher probabilities of exceedance for the same value of the spectral displacement of performance points, but as the seismic output increases the contrary situation occurs. It is also possible to observe that as the number of storey increases the range of spectral displacements where the updated curves return higher values probabilities of exceedance tend to become larger.

The above findings highlight the importance of performing refined calibration/validation exercises in seismic risk assessment in order to perform rational engineering decision-making.

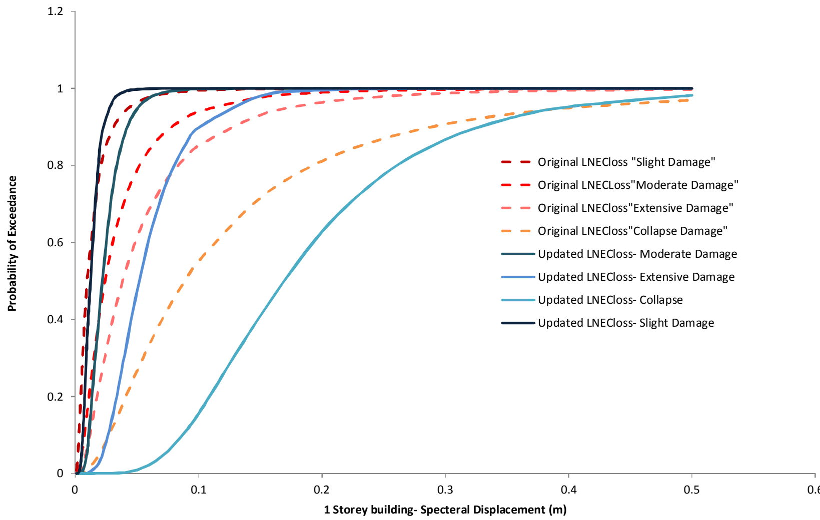

Fig. 6 - Original and updated fragility curves for 1 storey buildings.

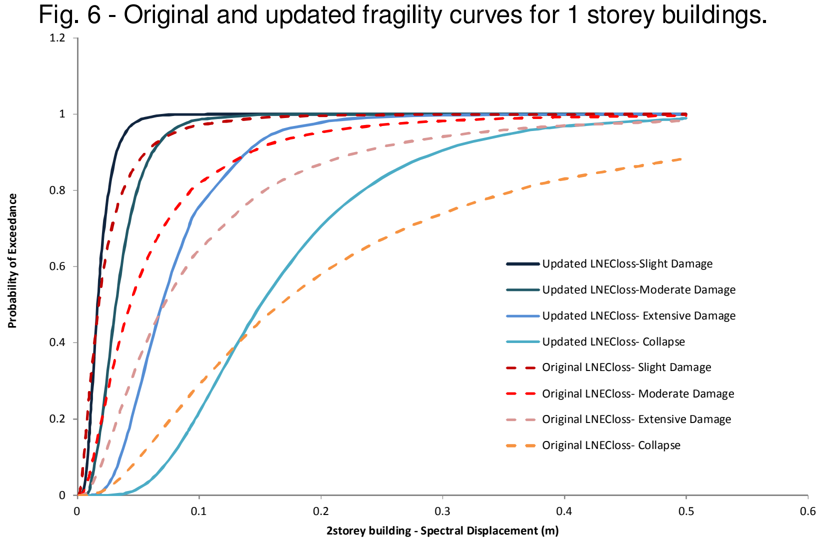

Fig. 7 - Original and updated fragility curves for 2 storey buildings.

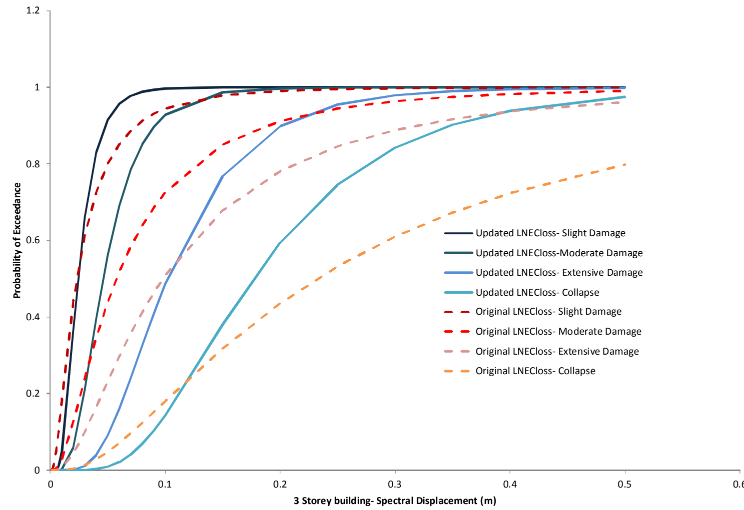

Fig. 8 - Original and updated fragility curves for 3 storey buildings.

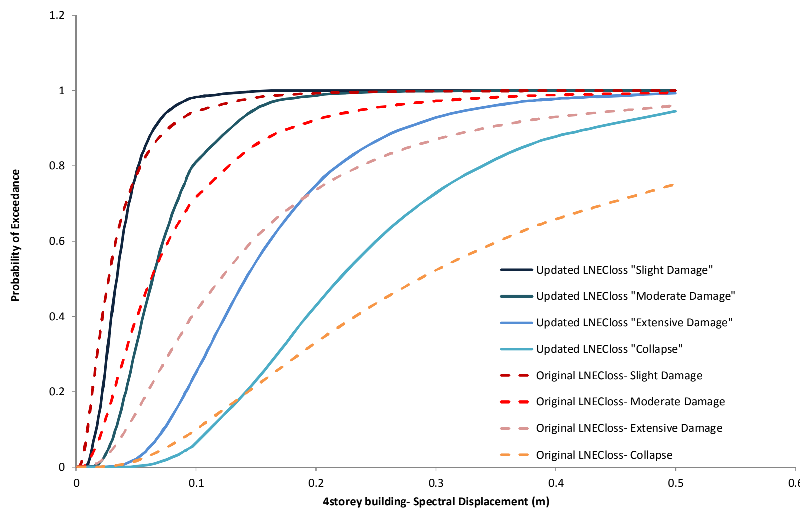

Fig. 9 - Original and updated fragility curves for 4 storey buildings.

5. FINAL REMARKS

This study presents new fragility curves for the Portuguese pre-seismic code reinforced concrete buildings, for four damage states and compares them with fragility curves that are included in LNECLoss and used in previous studies of seismic risk assessment for Portugal.

Although not here presented, fragility curves, using the same methodology described in this paper, were also obtained for four different retrofit strategies for RC buildings: (i) column jacketing, (ii) FRP column wrapping, (iii) execution of new RC walls and (iv) installation of structural steel brace elements.

How this new fragility curves will influence the seismic risk of the metropolitan area of Lisbon, is a work in progress, together with the seismic risk assessment using fragility curves for different retrofit strategies.

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