Seismic Loss Estimation and Strengthening of an old RC building in Lisbon

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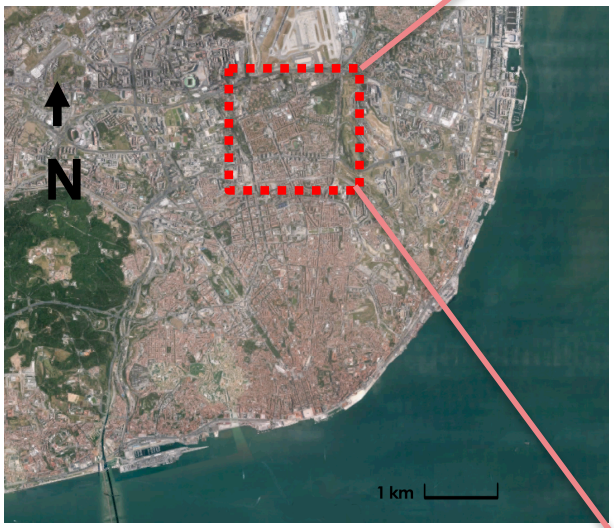
Motivation

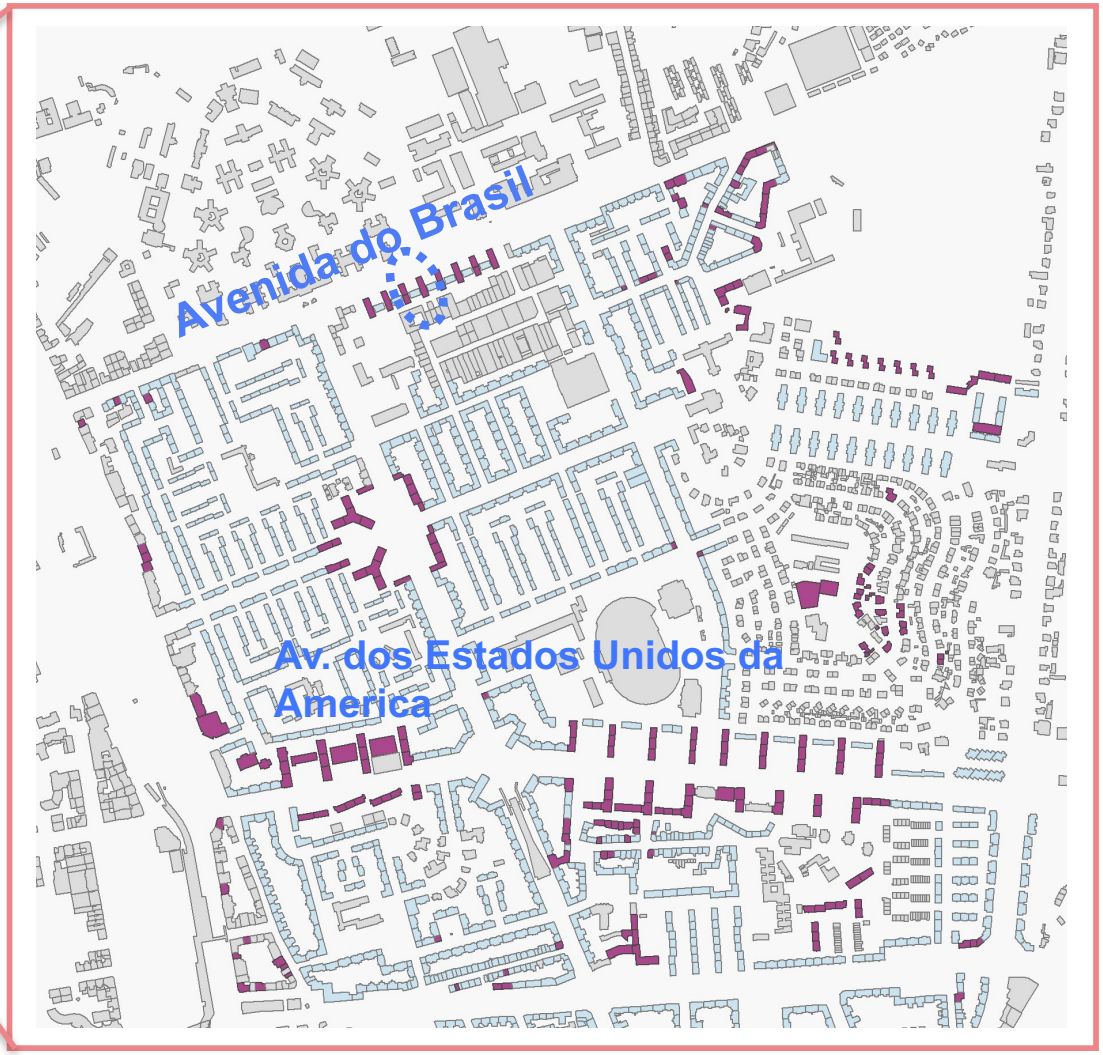
- Reinforced Concrete (RC) old frame and wall-frame structures represent a high percentage of building stock.
- They were constructed before the introduction of modern seismic codes without considering appropriate seismic criteria.

Main goal of this PhD Work

- Vulnerability assessment of old RC wall-frame buildings built between 1960 and 1980 in Lisbon;
- Development of a model that can account for the main features of old RC frame-wall structures, such as
  - ✓Infills walls;
  - ✓Reinforcement with smooth bars
  - ✓Torsional behaviour.
- Design of strengthening solutions, including cost-benefit analysis

Alvalade district





- Old RC frame buildings
- Other typologies

RC wall-frame buildings

Characteristics:

(i) from 8 to 12 floors;

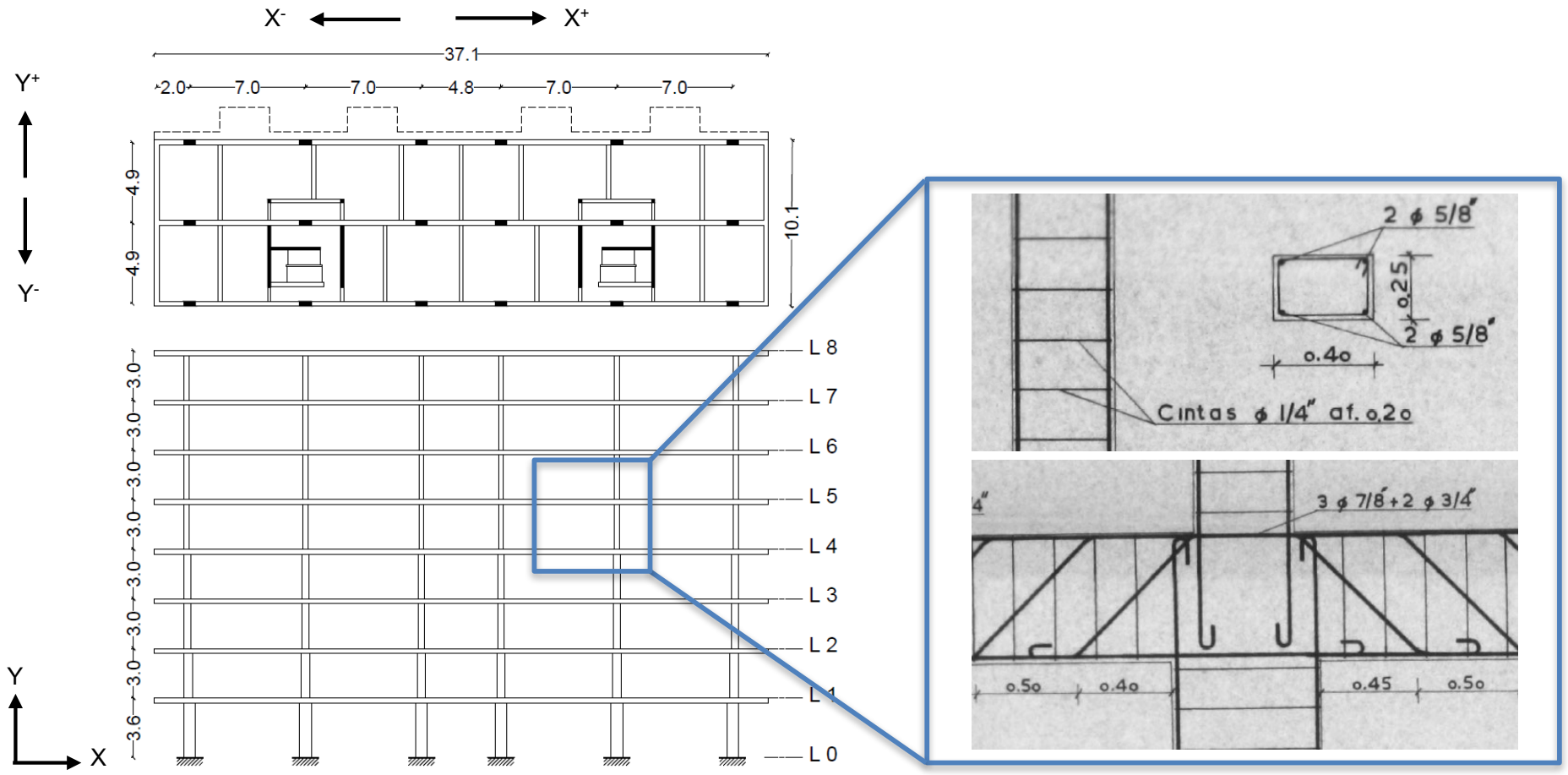
(ii) open ground storey and infills in the upper storeys (pilotis type building);

(iii) columns mainly oriented in one direction;

(iv) eccentric RC core walls (stair cases);

(v) smooth reinforcement bars.

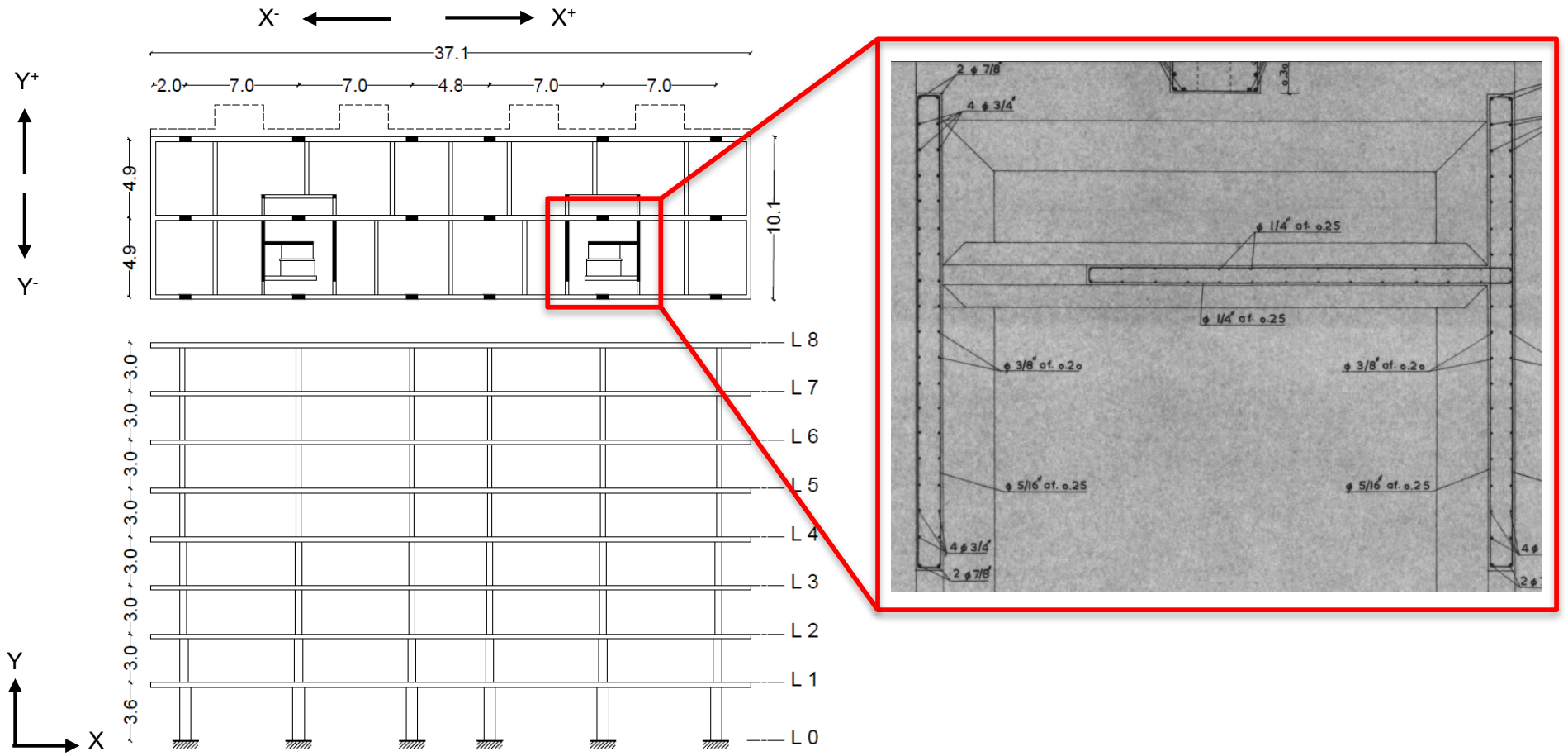
Case study



Inadeguate reinforcement detailing

- Insufficient reinforcement ties
- Size and reinforcement of columns varies in each floor
- Smooth longitudinal reinforcing bars

Case study



RC walls

- Do not present confined boundary elements
- Total reinforcement is always lower than 1%

Retrofitting measures and criteria

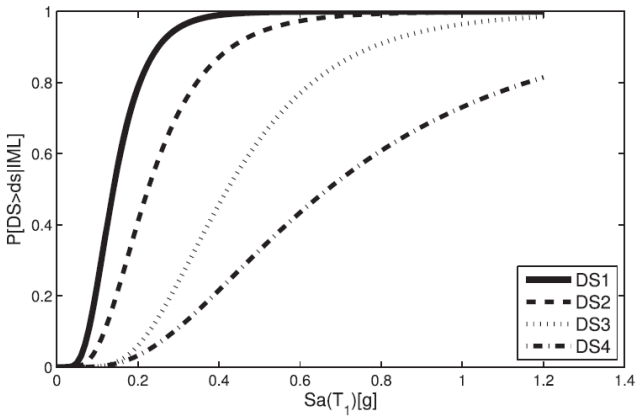
- Assessment of an existing building will reveal the deficiencies at local and global level
- Retrofitting measure will be selected to improve the performance of the building
- There are two main objectives in seismic retrofit, i.e. to reduce demand or to increase capacity, and three main properties to examine: strength, stiffness and deformation capacity.

Non-technical criteria

- The optimal retrofit solution should take into account additional practical and socio-economic aspects. These include (CEN 2005, Fardis 2009, FEMA 2006):
- Economic losses (repair or replacement losses)
- Disruption of use
- Availability of materials, technology and workmanship; …

Methodology to compute losses

- Fragility and consequence model



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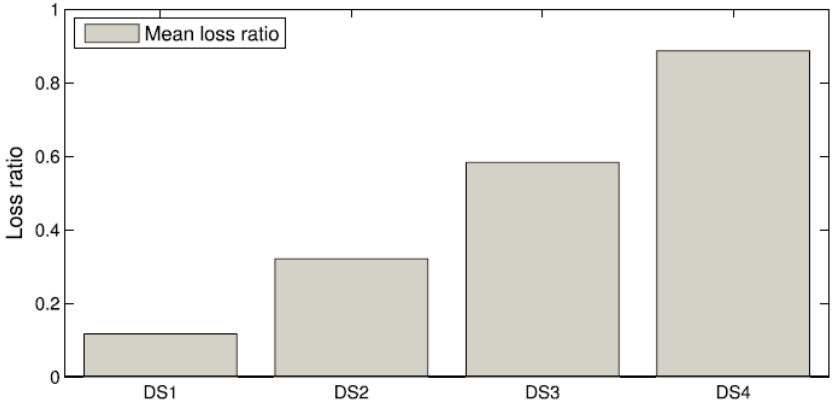
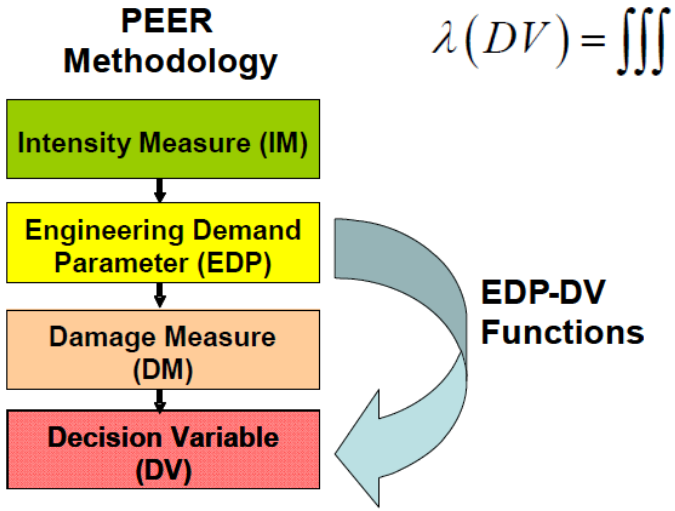


Performance level	Performance criteria
DS1 Light Damage	There shall not be any column or shear walls beyond immediate occupancy level.
DS2 Moderate Damage	10% of columns or shear walls has yielded
DS3 Significant Damage	More than 80% of the columns at the ground floor have yielded (soft storey mechanism)
	None of the structural elements must have reached the ultimate capacity
DS4 Collapse	More than 80% of the columns at the ground floor have reached their ultimate capacity.

Loss estimation

The PEER established a fully probabilistic framework to estimate damage and monetary losses in 4 steps:

1. Generate a seismic hazard curve and define the ground shaking in terms of an IM
2. Computing EDPs from structural analysis response of the building
3. Produce damage measure (DMs) using fragility functions
4. Define economic losses based on repair and replacement costs (decision variables DV)



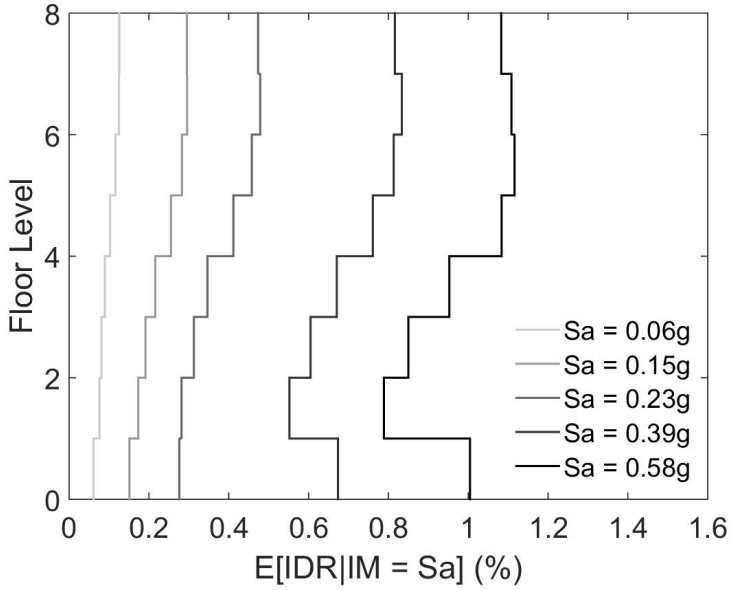
$$\lambda(DV) = \iiint G(DV|DM)\,dG(DM|EDP)\,dG(EDP|IM)\,d\lambda(IM)$$

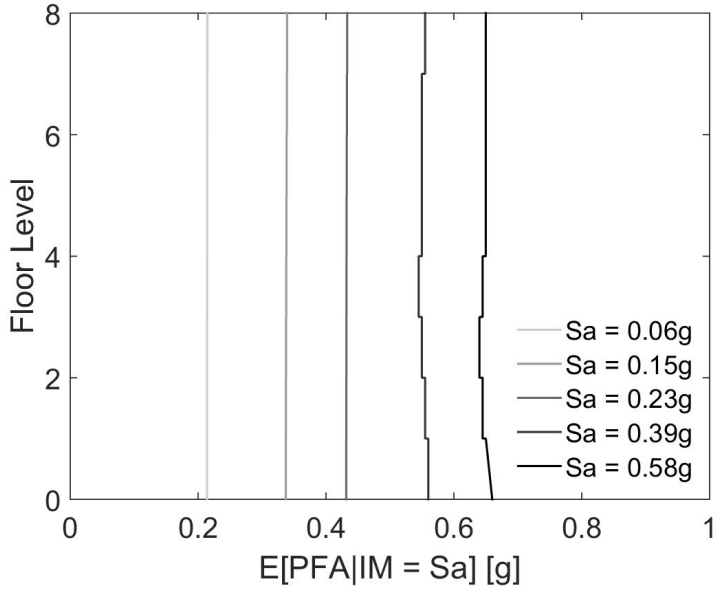
Engineering Demand Parameters

- Nonlinear response history-analyses were performed using a **Multiple Stripe Analysis**.
- The ground motions for each IM were selected using a **Conditional Mean Spectrum** approach

IM: 5% damped pseudo-spectral acceleration Sa($\overline{T}$)

EDP: **Inter-storey Drift Ratio** (IDR) and **Peak Floor Acceleration** (PFA)

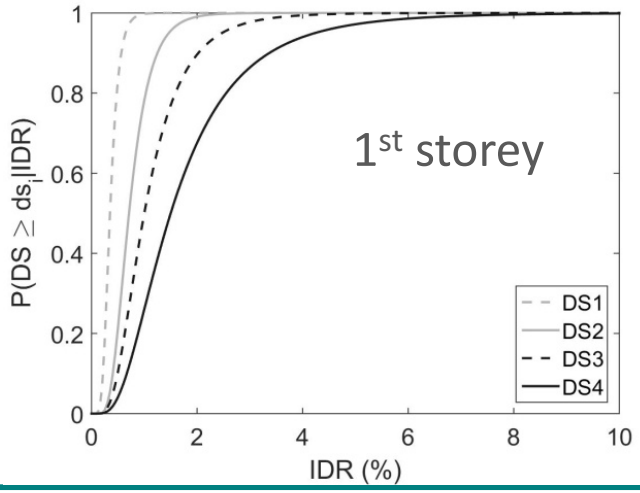


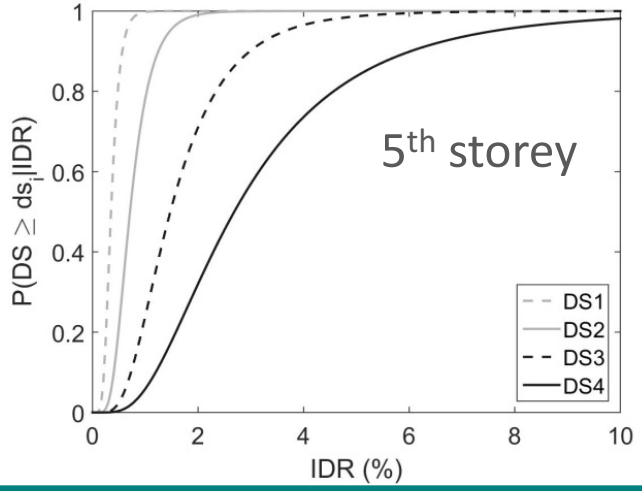


Damage analysis – Structural elements (Columns)

Component based fragility functions (Aslani and Miranda, 2005)

Damage state	Median (%IDR)	σ
DS1: Light Cracking	0.35	0.37
DS2: Severe Cracking	0.71	0.44
DS3: Shear Failure	$\overline{IDR}_{DS3} = \frac{1}{0.26\left(\frac{P}{A_g f_c' \rho''}\right) + 25.4} \geq \frac{1}{100}$	0.55
DS4: Loss of Vertical Carrying Capacity (Collapse)	$\overline{IDR}_{DS4} = \frac{1}{0.2\left(\frac{P}{A_g f_c' \rho''}\right) + 4.6} \leq \frac{1}{10}$	$\sigma_{Ln\ IDR_{DS4}} = 0.68 \exp\left[-\frac{29.4}{\left(\frac{P}{A_g f_c' \rho''}\right)}\right] \geq 0.1$





Damage analysis – Structural elements (RC Walls)

Component based fragility functions were derived using a **Monte Carlo simulation** (FEMA P-58) and **Nonlinear Pushover analysis**

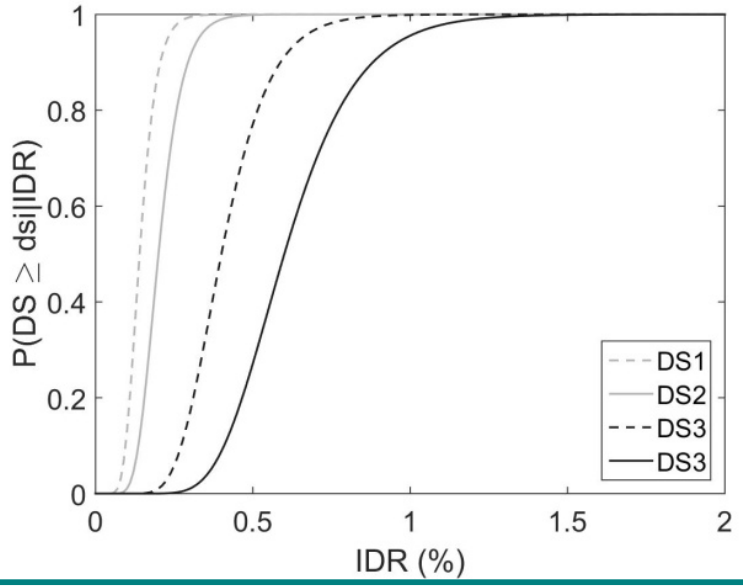
Damage state	Median (%IDR)	σ
DS1: Light Cracking	0.14	0.30
DS2: Severe Cracking	0.20	0.30
DS3: Shear Failure	0.40	0.30
DS4: Loss of Vertical Carrying Capacity (Collapse)	0.52	0.30

$$\overline{IDR}_{DS1} = 0.7 \cdot D_y$$

$$\overline{IDR}_{DS2} = D_y$$

$$\overline{IDR}_{DS3} = D_u$$

$$\overline{IDR}_{DS4} = 1.3 \cdot D_u$$



Damage analysis – Repair costs

Damage state	Repair Action	Unit	Costs [€/unit]
DS_1 Light Cracking	Cleaning cracks' interior	m	3.64
	Surface coating	m^2	72.60
DS_2 Severe Cracking	Cleaning cracks' interior	m	3.64
	Epoxy crack injection	m	265.49
	Patching spalled concrete	m^2	72.60
DS_3 Shear Failure	Cleaning cracks' interior	m	3.64
	Rebar replacement	each	51.14
	Epoxy crack injection	m	265.49
	Concrete spall repair	m^2	72.60
	RC jacketing (only RC walls)	m	300

Damage analysis – Non Structural elements

Storey based fragility functions provided by HAZUS

	Drift Sensitive		Acceleration Sensitive	
Damage state	**Median (IDR)**	**σ**	**Median (%g)**	**σ**
DS1: Slight	0.004	0.50	0.20%	0.50
DS2: Moderate	0.008	0.50	0.40%	0.50
DS3: Extensive	0.025	0.50	0.8%	0.50
DS4: Complete	0.050	0.50	1.6%	0.50

Cost of non-structural components has been estimated as a percentage of the total construction cost of the building (FEMA 2015, Ramirez and Miranda, 2012)

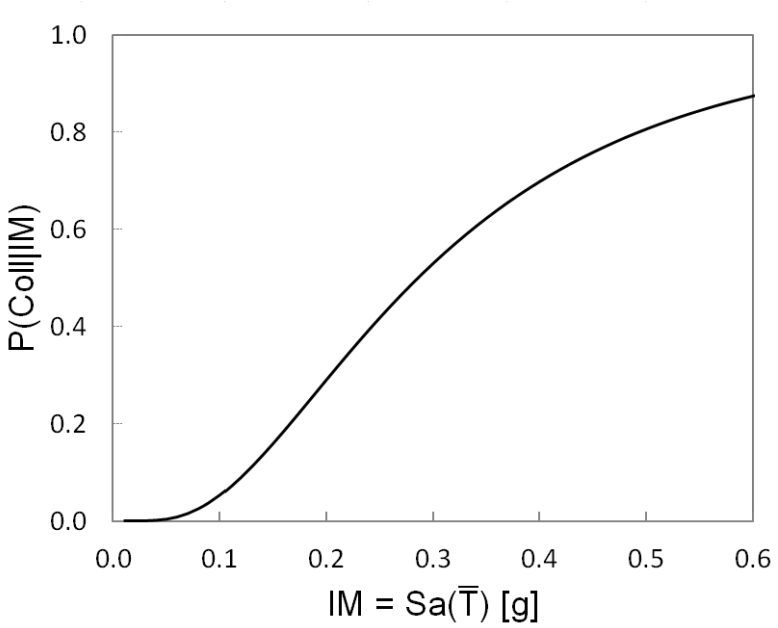
Drift Sensitive - non structural components 40%

Acceleration Sensitive - non structural components 40%

Loss analysis

$$E[Loss_T|IM] = E[Loss|Coll] \cdot P(Coll|IM) + P(NColl|IM) \cdot (E[Loss_{Str}|IM] + E[Loss_{NonStr}|IM])$$

The probability of collapse was assumed to be equal to the largest probability of any structural element that can lose its vertical carrying capacity (DS4):

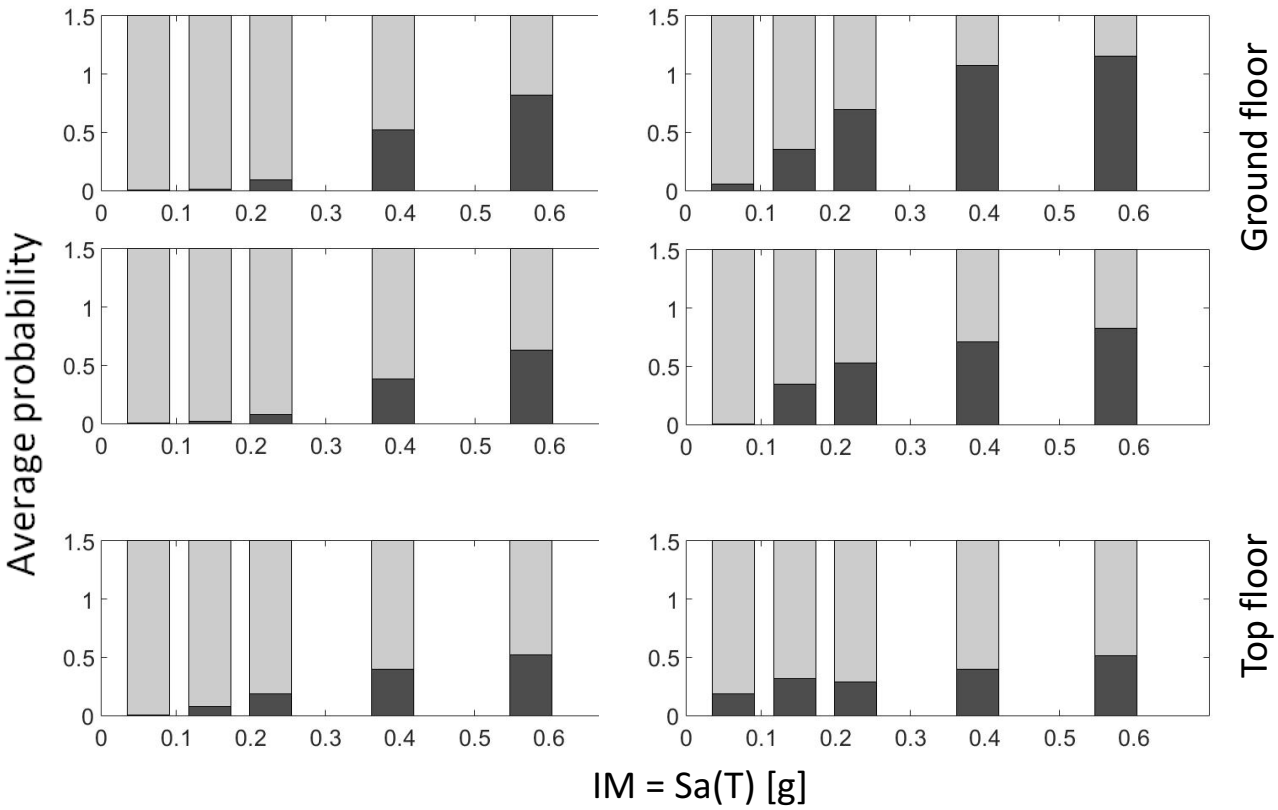


Number of storeys	8
Footprint	10.1 x 37.1
Area (m^2)	374.1
Cost per m^2 (€/m^2)	603
Replacement cost (€) ***E* [*Loss*|*Coll*]**	**1807600**

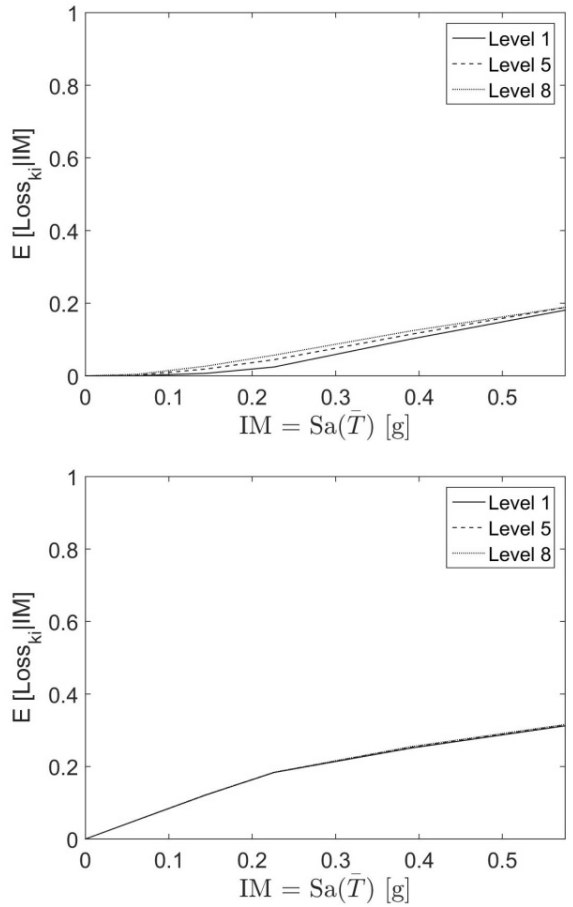
Loss analysis

$$E[Loss_T|IM] = E[Loss|Coll] \cdot P(Coll|IM) + P(NColl|IM) \cdot (E[Loss_{Str}|IM] + E[Loss_{NonStr}|IM])$$

$E[Loss_{Str}|IM]$



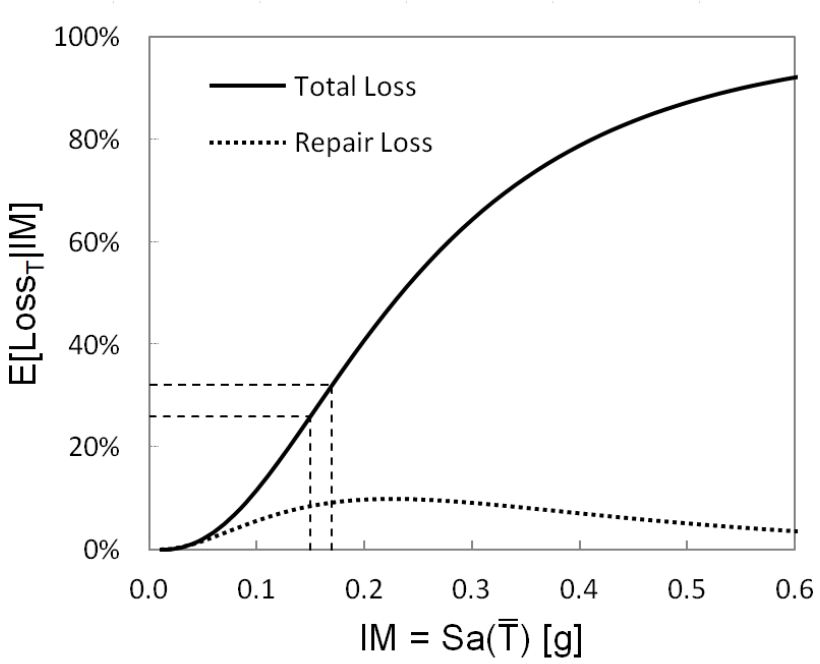
$E[Loss_{NonStr}|IM]$

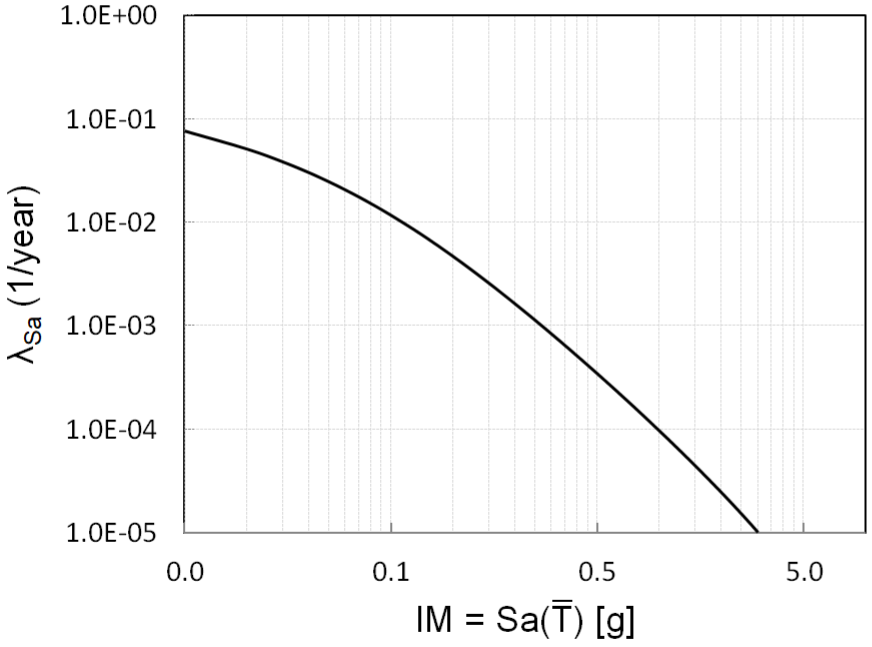


Loss analysis

$$E[Loss_T|IM] = E[Loss|Coll] \cdot P(Coll|IM) + P(NColl|IM) \cdot (E[Loss_{Str}|IM] + E[Loss_{NonStr}|IM])$$

The expected loss in a building can be used together with the seismic hazard curve to estimate the **Expected Annual Loss (EAL)** that is equal to 0.71% of the replacement value of the case study building.





Seismic hazard curves for Lisbon (T= 0.9 s)

Work done

The current state of the research involves estimation of economic losses in 4 steps:

- Step 1: Nonlinear dynamic analysis are performed on the structural model at increasing level of ground motion intensity
- Step 2: The results from the structural analysis are employed to compute Engineering demand parameters.
- Step 3: Damage to individual components is estimated using fragility functions for each component.
- Step 4: Economic losses are evaluated based on repair and replacement cost of damaged building components

Future developments

- This work will be repeated for the strengthened structures.
- Eventually a cost-benefit analysis will be developed in order to evaluate the actual convenience in choosing one of the examined strengthening strategies.

Thank you!

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