Seismic retrofit options for an old RC wall-frame building in Lisbon: impact on loss estimation and cost-benefit analysis

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1. Motivation

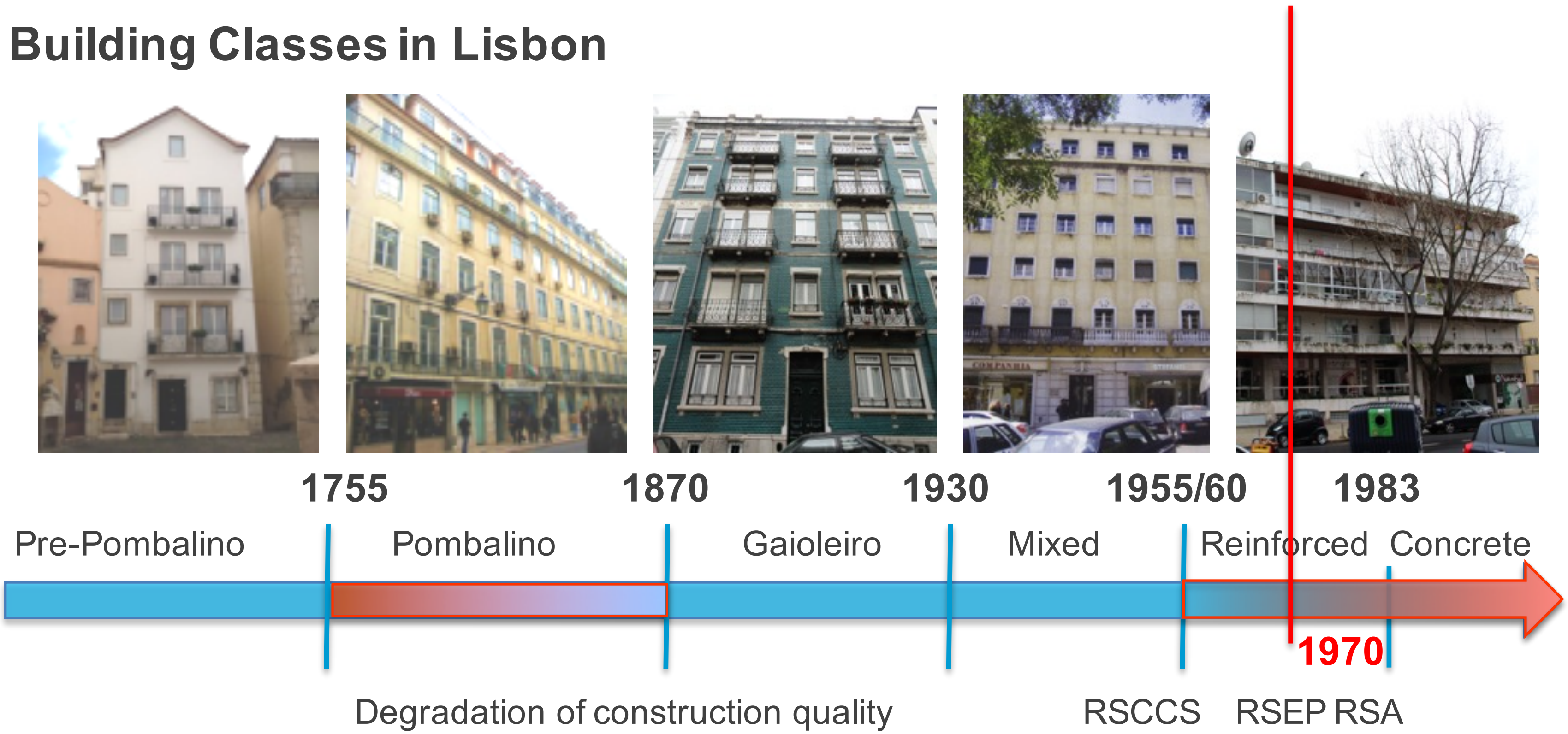
- **Seismic vulnerability evaluation** and **strengthening** of existing buildings is key to reduce the levels of physical damage, loss of life and economic impact of future seismic events.
- **RC framed** and **dual wall-framed structures** designed according to old codes represent an important fraction of the building stock in Lisbon.

Objectives

1. Characterization of the **wall-frame building typology**, focusing on the main features and structural behaviour;
2. Definition of modelling approach and discussion on modelling issue;
3. Addressing various source of uncertainty;
4. Analysis of the seismic safety of the building and definition of damage states and the likely collapse mechanisms;
5. Definition of a methodology for the **economic loss assessment** and **vulnerability assessment**;
6. Investigation of the effectiveness of **retrofitting strategies**.

1. Introduction

RC Building Classes in Lisbon



Adapted from (Pina and Campos e Costa, 2018, OE)

- The first design codes that explicitly consider provisions for the seismic action date from 1958 (RSCCS 1958) to 1961 (RSEP 1961)
- In 1983 a new and more demanding code was introduced (RSA 1983)
- Until 1980 – use of smooth rebars.

1. Introduction

RC Buildings in Lisbon – Area of Study

Area delimited by:

Avenida Brasil, Avenida Gago Coutinho, Avenida da República e **Alameda D. Afonso Henriques**

1. Introduction

Buildings in Lisbon – Area of Study

1639 Buildings analysed

17.4% RC Framed/ Wall-framed Buildings

Interior Walls

Infills –
Brick Masonry

External Walls

Infills –
Brick Masonry

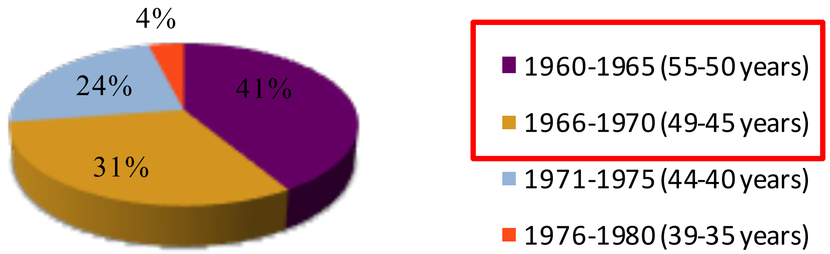
Floors

266 **RC flat slabs**
10 Precast slabs
9 Void Slabs

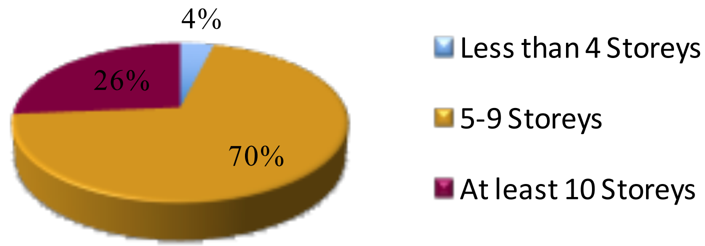
1. Introduction

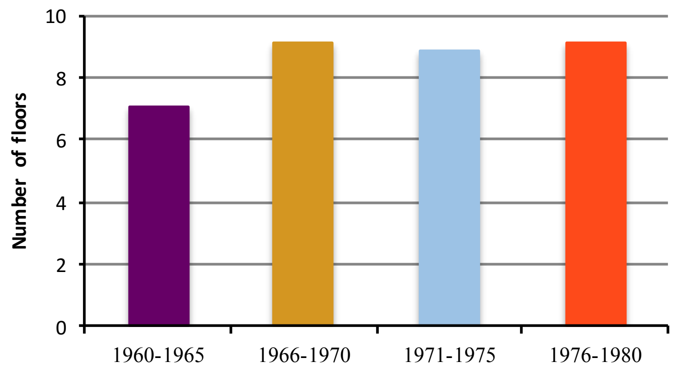
RC Buildings in Lisbon – Area of Study

Date of Construction



Number of Storeys





- **Increase** of number of storeys with the year of construction

2. Performance-based cost-benefit assessment

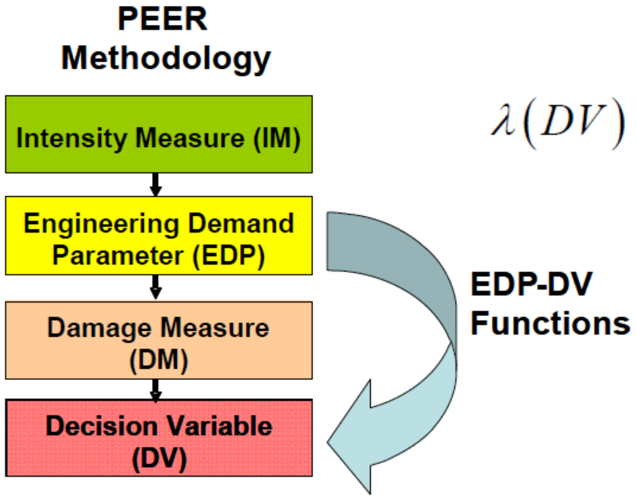
A **building specific loss estimation methodology** is applied to estimate economic loss and the **PEER** performance-based earthquake engineering assessment procedure to estimate damage and monetary losses in 4 steps:

1. **Hazard Analysis**: Generate a seismic hazard curve and define the ground shaking in terms of an Intensity Measure (IM)

2. **Structural Analysis**: Computing **Engineering Demand Parameters** (**EDPs**) from structural analysis of the building

3. **Damage analysis**: Produce **Damage Measure** (DMs) using fragility functions

4. **Loss Analysis**: Define economic losses based on repair and replacement costs (decision variables DV)

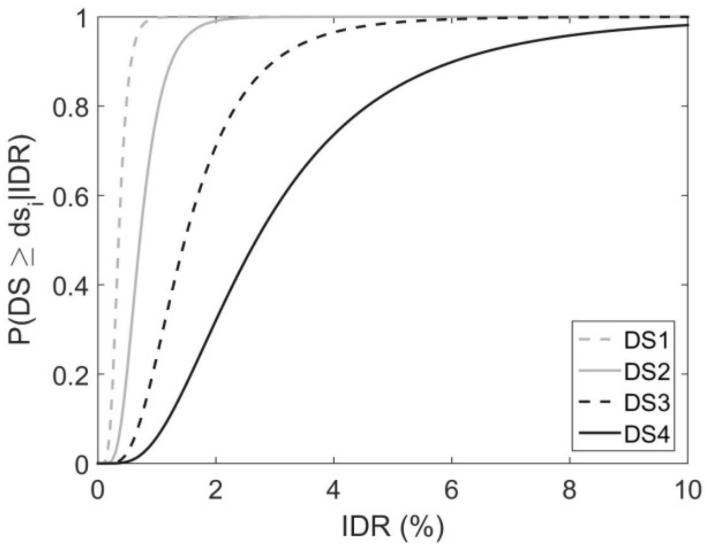


$$\lambda(DV) = \iiint G(DV|DM)\,dG(DM|EDP)\,dG(EDP|IM)\,d\lambda(IM)$$

2. Performance-based cost-benefit assessment

Damage Analysis

Columns: Component based fragility functions from Aslani and Miranda (2005).



Damage state	Median (% IDR)
Light Damage (DS1)	0.35
Moderate Damage (DS2)	0.71
Severe Damage (DS3)	$\overline{IDR}_{DS3} = \frac{1}{0.26\left(\frac{P}{A_g f'_c \rho''}\right) + 25.4} \geq \frac{1}{100}$
Collapse (DS4)	$\overline{IDR}_{DS4} = \frac{1}{0.2\left(\frac{P}{A_g f'_c \rho''}\right) + 4.6} \leq \frac{1}{10}$

2. Performance-based cost-benefit assessment

Damage Analysis

RC walls : Analytical evaluation of fragility functions

Nonlinear static analyses

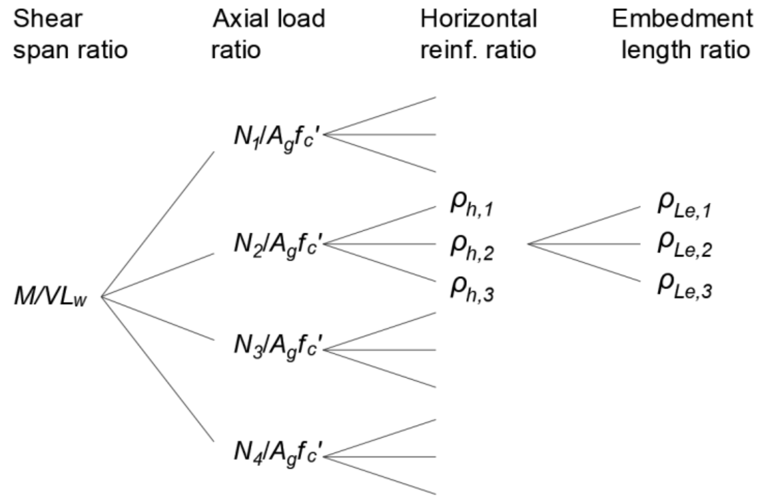
Damage states

DS1: flexural cracking

DS2: first yield

DS3: ultimate strain in the unconfined concrete or strain in rebar after yielding

DS4: bounded by ultimate strain in concrete or in steel rebar or shear failure

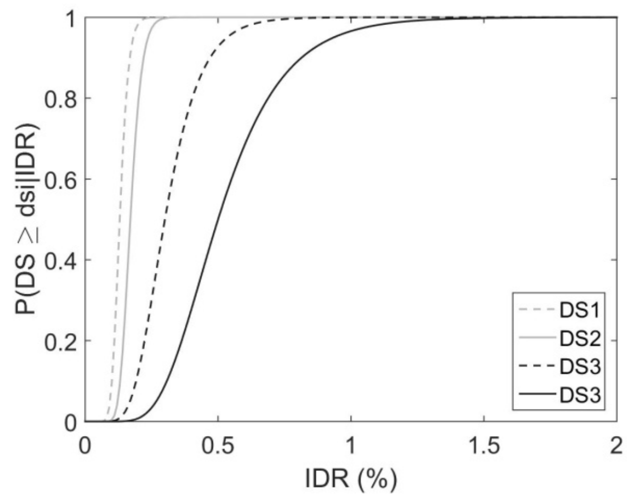


$$\overline{IDR}_{DS1} = 0.0013$$

$$\overline{IDR}_{DS2} = 0.0015 + 0.05\rho_h$$

$$\overline{IDR}_{DS3} = 0.001 + 0.054\rho_h + 0.005\rho_{Le} - 0.003\frac{N}{A_g f_c'}$$

$$\overline{IDR}_{DS4} = 0.002 + 4\rho_h - 0.035\frac{N}{A_g f_c'}$$



2. Performance-based cost-benefit assessment

Loss analysis - the total expected loss $E[Loss_T|IM]$ in a building, as a function of the ground motion intensity, IM, was calculated as the sum of 3 components:

$$E[Loss_T|IM] = E[Loss|C] \cdot P(C|IM)$$

losses resulting **if the building collapses**

$$+E[Loss|NC \cap R, IM]\ \{1 - P(D|NC, IM)\} \cdot \{1 - P(C|IM)\}$$

losses associated **with repairs given that the structure has not collapsed** (NC) at a given ground motion intensity

$$+E[Loss|NC \cap D] \cdot P(D|NC, IM) \cdot \{1 - P(C|IM)\}$$

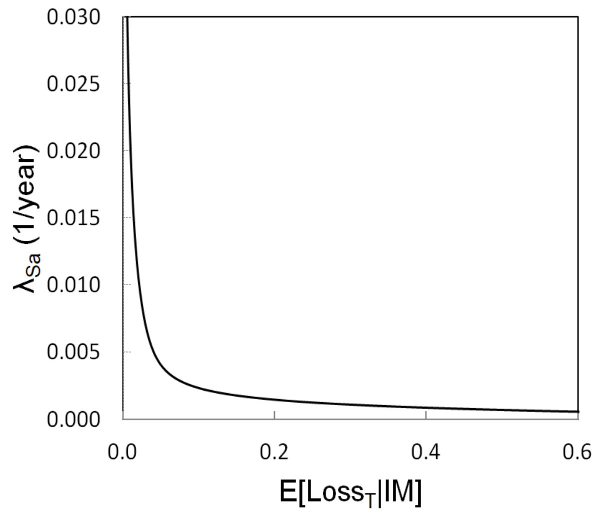
losses resulting from having to demolish the building due to excessive residual drifts

2. Performance-based cost-benefit assessment

Evaluation of the **expected annual loss** (**EAL**) of the building, which corresponds to the economic loss that, on average, can occur every year. The **EAL** provides quantitative information to assist stakeholders in making risk management decisions and is used in the insurance sector to calculate the insurance premium.

EAL is obtained by integrated the expected losses $E[Loss_T|IM]$ over the entire hazard curve

$$EAL = \int_0^\infty E[Loss_T|IM] \cdot d\lambda(IM)$$



$\lambda(IM)$ is the mean annual frequency of exceeding a ground motion intensity

3. Case study – RC wall-frame building

(i) Designed and built in the 1960's

(ii) From 8 to 12 floors

(iii) Infills are distributed irregularly along the height – open ground storey and infills in the upper storeys (*pilotis* type building)

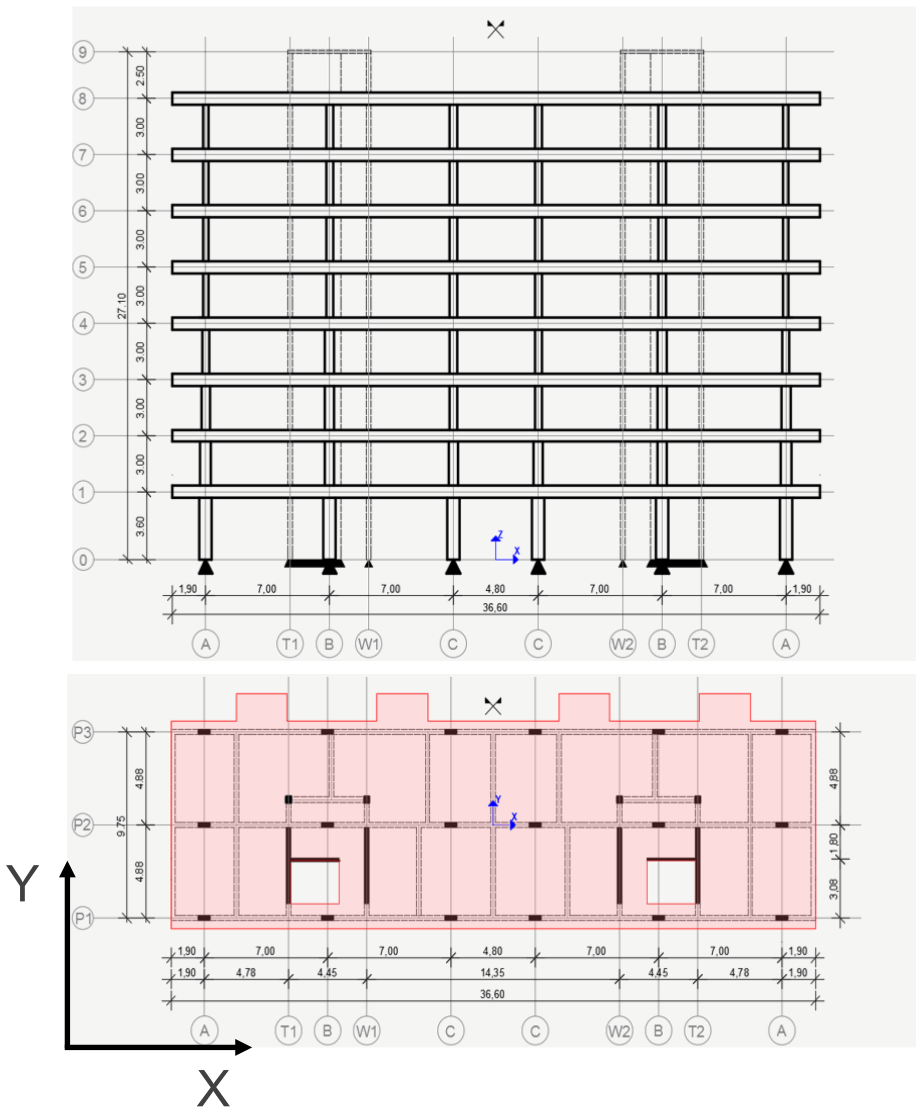
(iv) Smooth reinforcement bars

(v) Columns mainly oriented in one direction

(vi) Eccentric RC core walls (stair cases)

(vii) Beams framing eccentrically to the columns

(viii) The structure is symmetric along the Y direction and moderately asymmetric along the X direction



3. Case study – Numerical modelling

Nonlinear response-history analyses were performed using a **Multiple Stripe Analysis** and adopting a conditional mean spectrum

Final numerical modelling

3D Modelling

Force based beam-column elements and fibre modelling approach are employed

Uniaxial material models

Concrete - Popovics model
Steel - Menegotto e Pinto

Development of a model that can account for the main features of old RC frame-wall structures

Infills walls (were modelled by means of two diagonal struts)
Reinforcement smooth bars and small embedment length

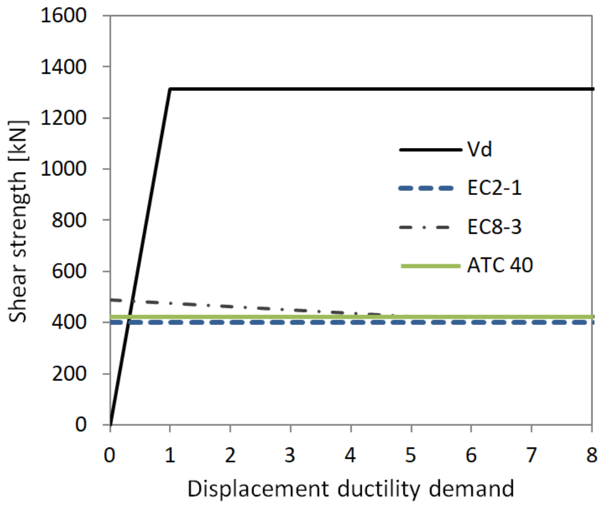
Caruso C, Bento R, Sousa R and Correia AA, **2018**: Modelling strain penetration effects in RC walls with smooth steel bars. Magazine of Concrete Research, https://doi.org/10.1680/jmacr.18.00052

4. Strengthening

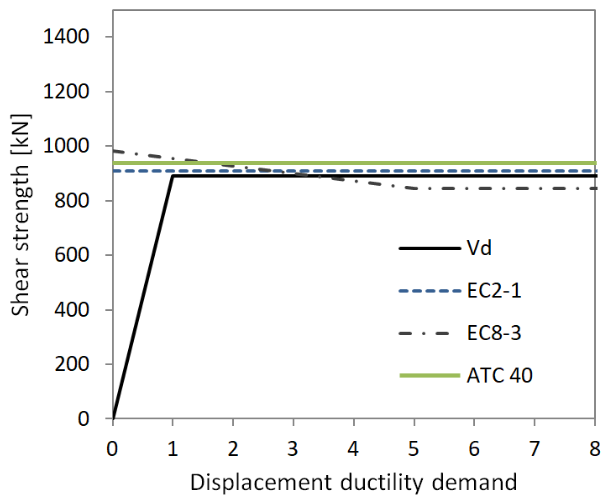
Criteria for strengthening

- Retrofitting strategies are evaluated with the aim of improving the performance of the RC walls in the X direction, which are **more vulnerable to brittle shear failure and tend to cause earlier collapse of the building**.

- This is evident from the comparison between the shear strengths obtained with the expressions provided by EC8-3 and EC2-1 and ATC-40 and the shear demand (Vd) of the RC walls, obtained by means of nonlinear static analyses.



X - direction

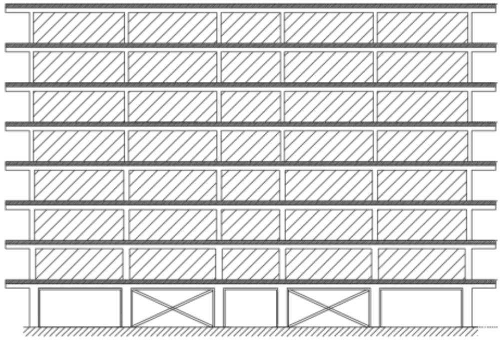


Y - direction

4. Strengthening

Two local methods of retrofitting were used:

1. Partial strengthening at the open ground storey with **steel braces**



Bay's dim [m]	Brace type	λ	N_{cr} [kN]	$N_{pl,Rd}$ [kN]	$N_{b,Rd}$ [kN]
7x3.6	CHS 219.1x5.9	1.30	716.4	983.7	681.3

Hot-rolled, Circular Hollow Section

2. **FRP-wrapping** of single elements (individual RC walls)

	n_f	$f_{dd,e}$ (kN)	$V_{Rd,f}$ (kN)
Fully wrapped	1	789	986
	2	**679**	**1697**
Side bonded	1	517	746
	5	**207**	**1496**

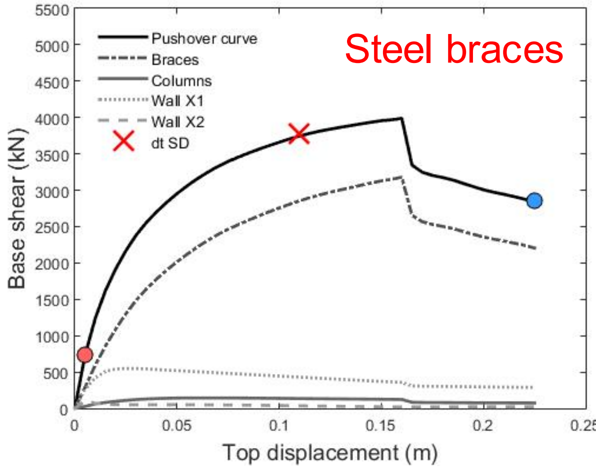
$$V_{Rd,f} = 0.9 \cdot d \cdot f_{fdd,e} \cdot 2 \cdot t_f \cdot (\cot\theta + \cot\beta) \cdot \frac{w_f}{s_f}$$

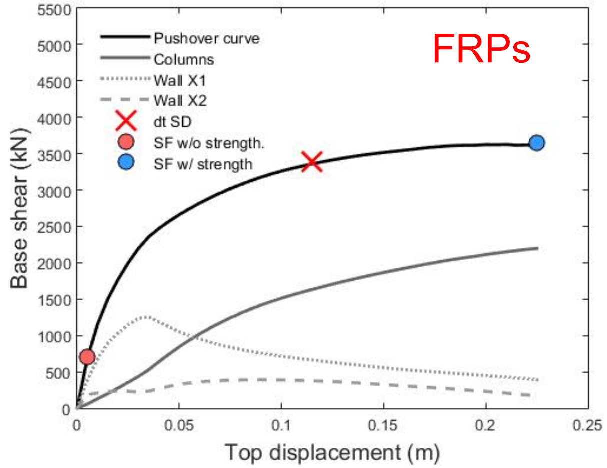
$$V_{Rd,f} = 0.9 \cdot d \cdot f_{fdd,e} \cdot 2 \cdot t_f \cdot \frac{\sin\beta}{\sin\theta} \cdot \frac{w_f}{s_f}$$

EC8-3

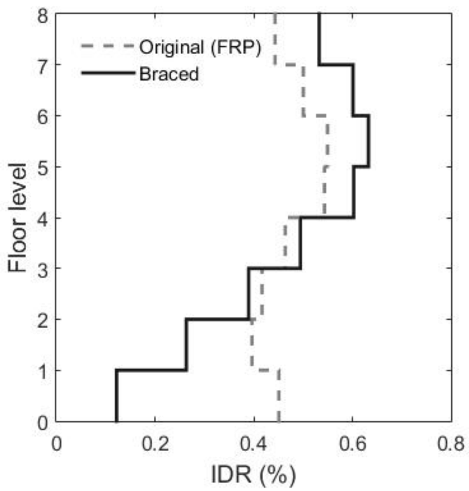
Retrofitting strategies - Results

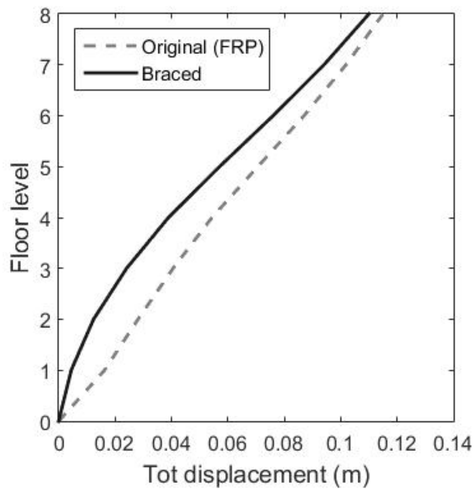
Pushover curves in the X direction for the retrofitted building with (left) steel braces and (right) FRP





Inter-storey drifts (IDR) (a) and lateral displacements profile (b)





Retrofitting strategies - Results

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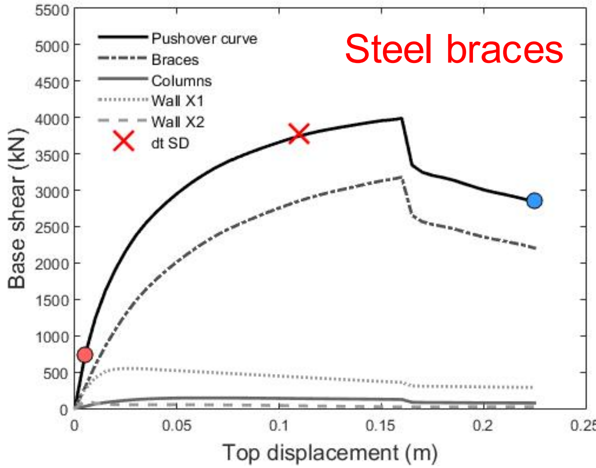
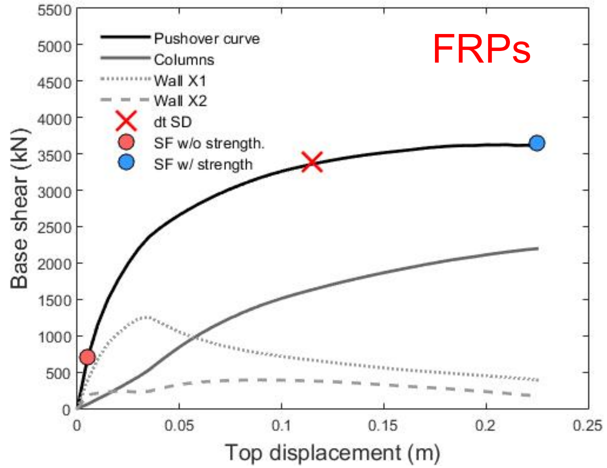
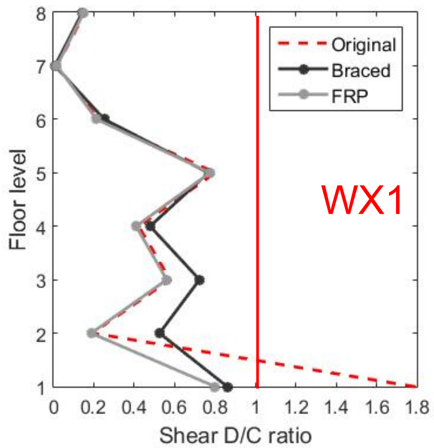
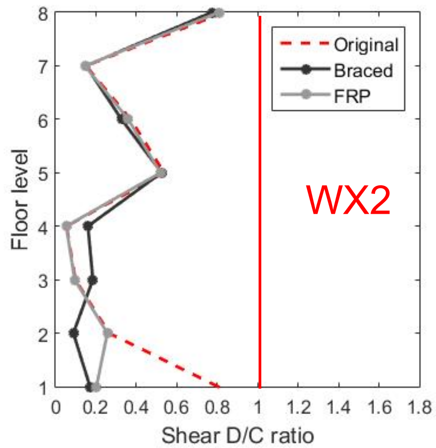




Shear D/C ratio lower than 1 in RC walls

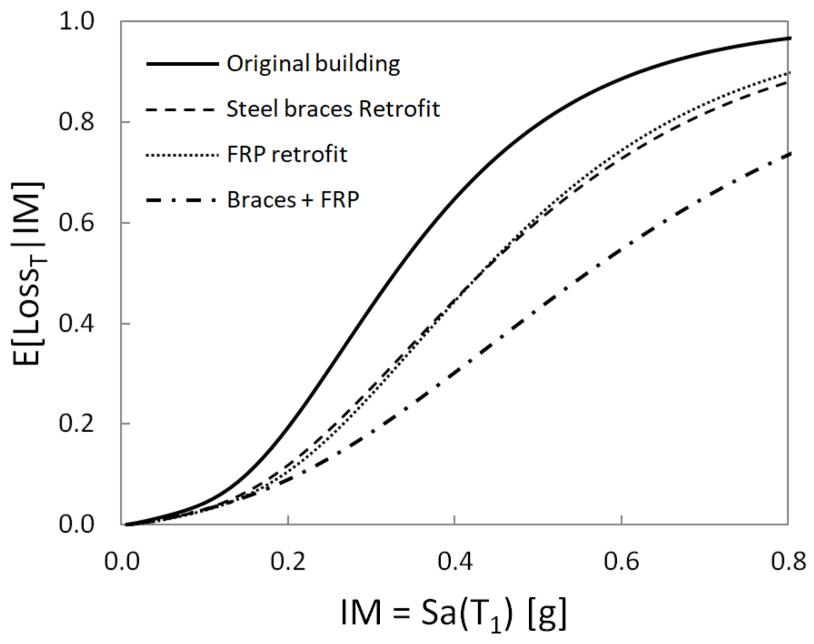




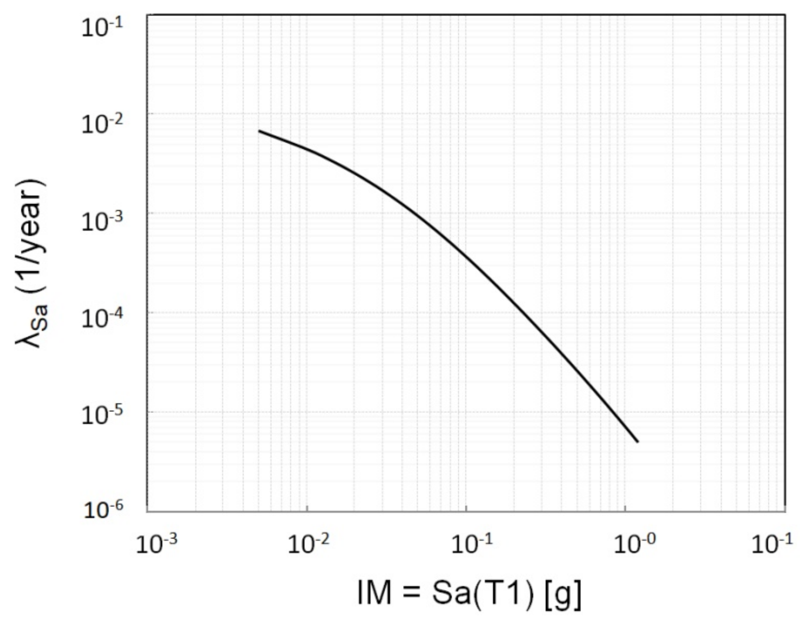
Shear Demand/Capacity ratio

Loss assessment

Through convolution of the **vulnerability curves** with **the seismic hazard curve** for the city of Lisbon, the **expected annual loss** (EAL) of the case study building is estimated.



Vulnerability curves



Seismic hazard curves for Lisbon, for a return period T1 = 0.89 seconds

Cost of retrofitting

Evaluation of the cost of each strengthening intervention is herein made.

The **indirect losses** are assessed considering only the costs of relocating the inhabitants for the downtime required to repair the building and evaluated as percentage of building replacement cost as to 0.40%/day.

Unit cost of retrofitting with FRP	Unit	Unit cost [€/unit]
Scaffolding	m^2	17.62
Demolition of interior partition wall	m^2	4.51
C-FRP laminates	m^2	97.88
C-FRP sheets	m^2	106.53
Reconstruction of interior partition wall	m^2	26.82
Plastering	m^2	4.29

Unit cost of retrofitting with steel braces	Unit	Unit cost [€/unit]
Scaffolding	m^2	17.62
Steel Bracings	kg	5.00

Benefit-cost

Benefits of seismic mitigation are evaluated in terms of **improved performance of the building,** as the difference in **net present value** (NPV) **of expected annual losses** for the retrofitted (NPV_R) and the original (NPV_O) buildings (Liel and Deierlein, 2013).

$$NPV = EAL \sum_{t=1}^{T} (1+r)^{-t}$$

(r = 1% - represents the discount rate and has been assumed equal to 1%, equal to the inflation rate in Portugal in 2018)

Benefit-Cost Ratio

$$\frac{Benefit}{Cost} = \frac{NPV_O - NPV_R}{Cost_{retrofit}}$$

	EAL (%)	Benefit (%)	Cost of retrofit (%)	Benefit-Cost Ratio	Break-even (years)
Original	0.164	-	-	-	-
X-braces	0.116	1.46	0.83	**1.76**	21
FRP	0.108	1.68	0.86	**1.29**	33
X-braces + FRP	0.096	2.05	2.03	**1.01**	50

5. Conclusions

- This work addressed strengthening measures for a old RC frame-wall building
- The purpose of this the study was to design **local seismic interventions**, applied to a group of members that suffer from structural deficiencies;
- **Seismic performance assessment** before and after rehabilitation has been evaluated;
- A **benefit-cost analysis** was performed, which showed that local methods of intervention are perhaps the only retrofitting possibility for two reasons:
    I. low cost of intervention;
    II. low downtime of the building during the retrofitting work.
- Future research shall include examination of additional case study buildings

Thesis Outline

Definition of mitigation strategies for the seismic risk reduction of old RC residential buildings

1. Introduction
2. Modelling strain penetration effects in RC walls with smooth bars
   - Caruso C, Bento R, Correia AA, Sousa R (2018) Modelling strain penetration effects in RC walls with smooth steel bars. Magazine of concrete research. Doi: 10.1680/jmacr.18.00052
3. Seismic assessment of an existing old frame-wall RC building in Lisbon – sensitivity analysis
4. Relevance of torsional effects on the seismic assessment of old RC frame-wall buildings
   - Caruso C, Bento R, Marino EM, Castro JM (2018) Relevance of torsional effects on the seismic assessment of an old RC frame-wall building in Lisbon. Journal of Building Engineering 19:459–471. Doi: 10.1016/j.jobe.2018.05.010
5. A contribution to the seismic performance and loss assessment of old RC wall-frame buildings
   - Caruso C, Bento R, Castro JM (2019) A contribution to the seismic performance and loss assessment of old RC wall-frame buildings. Engineering Structures. Doi: 10.1016/j.engstruct.2019.109369
6. Feasibility of retrofitting solutions for old RC wall-frame buildings
7. Final remarks and future work

THANK YOU

FOR

YOUR ATTENTION!

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