Development of Rapid Methods for Seismic Assessment of Existing Masonry Buildings

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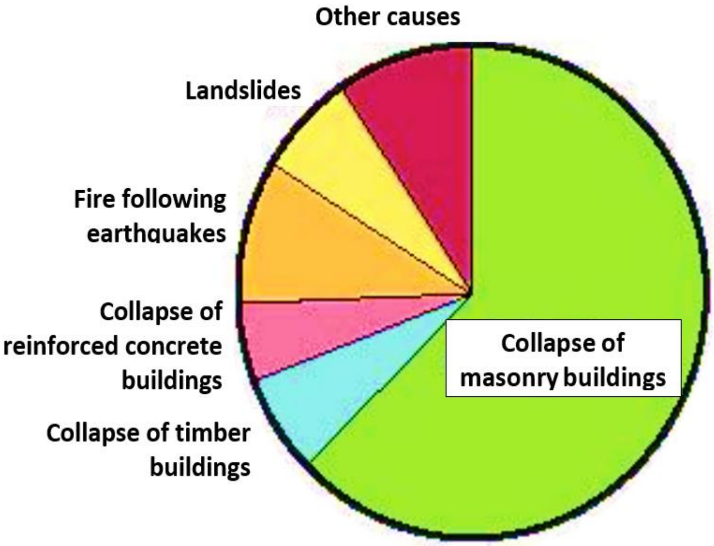
Motivation

- The major number of collapses caused by earthquake events occur in masonry buildings;
- Reduce the impacts and losses and conservation of built heritage;
- Most of the old masonry buildings in Portugal were designed only for gravity loads without considering the seismic effects (first regulation against earthquakes in 1958) ;
- Seismic assessment of buildings is mandatory since the publication of LD nº95/2019 and Ordinance nº302/2019.



Earthquake fatalities by cause (1900-1992) Coburn & Spence, 2002

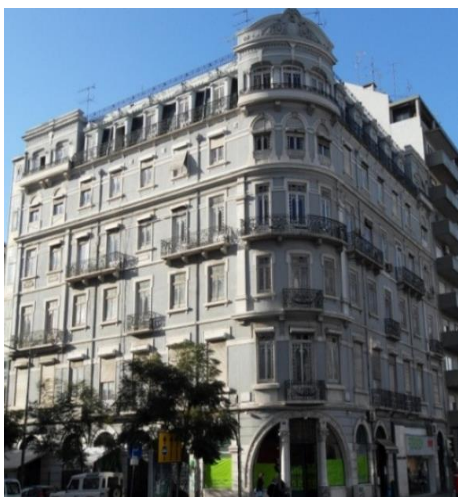
Research Objectives

- Seismic Vulnerability Assessment of Old Masonry buildings, identify building fragilities and reduce seismic risk.
- Propose Rapid methods for seismic assessment of masonry existing buildings, according to Eurocode 8 – part 3 (NP EN 1998-3:2017).

Overview of old masonry building stock

Pre-Pombalinos

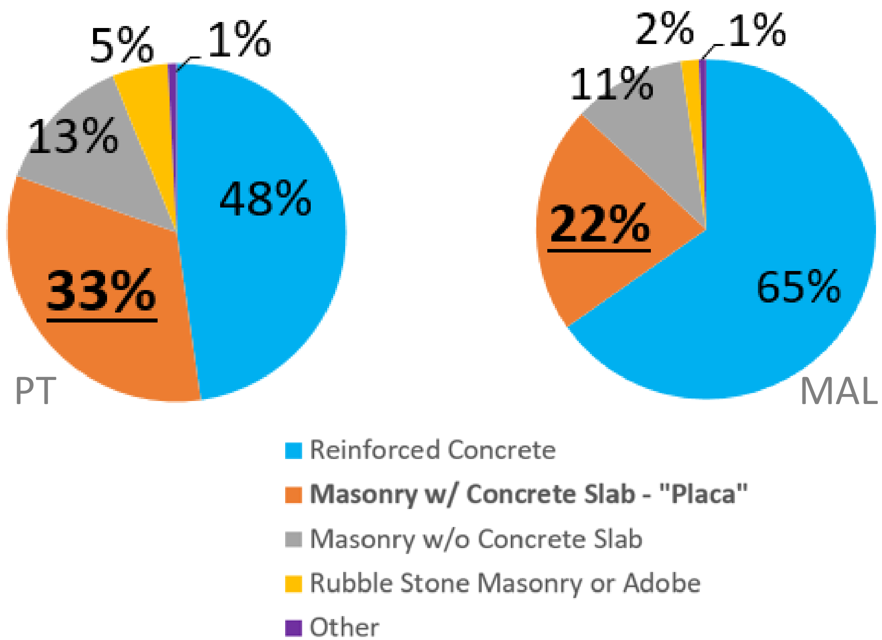
Pombalinos



Gaioleiros

Placa

Building typology	Construction period
Pre-Pombalinos	up to 1755
Pombalino	1755 to 1870
Gaioleiros	1870 to 1930
Placa	1930 to 1960



Eurocode 8-3: Assessment and retrofitting of buildings – Annex C

		Local Analysis	Global Analysis
Methods		Linear (lateral forces and modal response spectrum analysis)	Linear and Nonlinear (nonlinear static or dynamic)
Knowledge Level (KL) and confidence factor (CF) (depends on the information collected)		Limited (KL1): CF=1,35 Extended (KL2): CF=1,20 Comprehensive (KL3): CF=1,00	Extended (KL2): CF=1,20 Comprehensive (KL3): CF=1,00
Limit states (depends on the importance class and KL)		Damage Limitation (DL): Tr = 73years (class: III and IV)	Damage Limitation (DL): Tr = 73 years (class: III and IV) $\boxed{\text{Significant Damage (SD): Tr =308 years (class: all)}}$ Near Collapse (NC): Tr = 975 years (class: III and IV)
Verification (using mean properties μ)	**Ductile mechanisms μ/CF**	Yielding strength and deformation	**Linear:** base shear (only for DL) **Nonlinear:** roof displacement and verification in deformation (SD and NC) and strength (DL)
	Brittle mechanisms $\mu/(CF\gamma_m)$	Yielding strength	**Linear:** base shear (only for DL) **Nonlinear:** roof displacement and verification in strength (all Limit States)

Rapid methods for seismic assessment

Summary

Procedures to develop Rapid methodologies for seismic assessment of masonry buildings

1. **Geometry and materials**
   - Geometry based on a comprehensive and exhaustive survey (around 100 buildings);
   - Material properties with a wide range of allowable values to consider the variability in masonry characterization;
   - Database with 9000 buildings with different geometry and up to 5 stories height;
2. **Modeling and general assumptions**
   - Numerical modeling based on Macroelement - Tremuri (Gambarotta and Lagomarsino) ;
   - Macroelement calibrated through experimental cyclic tests;
   - Only in-plane mechanisms are simulated. The out-of-plane mechanisms are not considered or are prevented - NP EN 1998-3:2017;
   - Capacity curves obtained using nonlinear static analysis (performance-based);
   - Elastic response spectrum - NP EN 1998-3:2017 (4.1(1));
   - Bilinearization of capacity curve and performance points NP EN 1998-3:2017 (4.4.4.4)

Summary

Procedures to develop Rapid methodologies for seismic assessment of masonry buildings

3. **Probabilistic seismic analysis and reliability**
    - Performance points obtained for all capacity curves (*per se*), considering all seismic actions (onshore and offshore) defined in Eurocode, return periods up to 5000 years and soil types A, B and C;
    - Derive a relationship between the reliability index and seismic coefficient;
    - Analytical solution was obtained for the annual exceedance probability assuming an elastic-perfectly-plastic behavior;

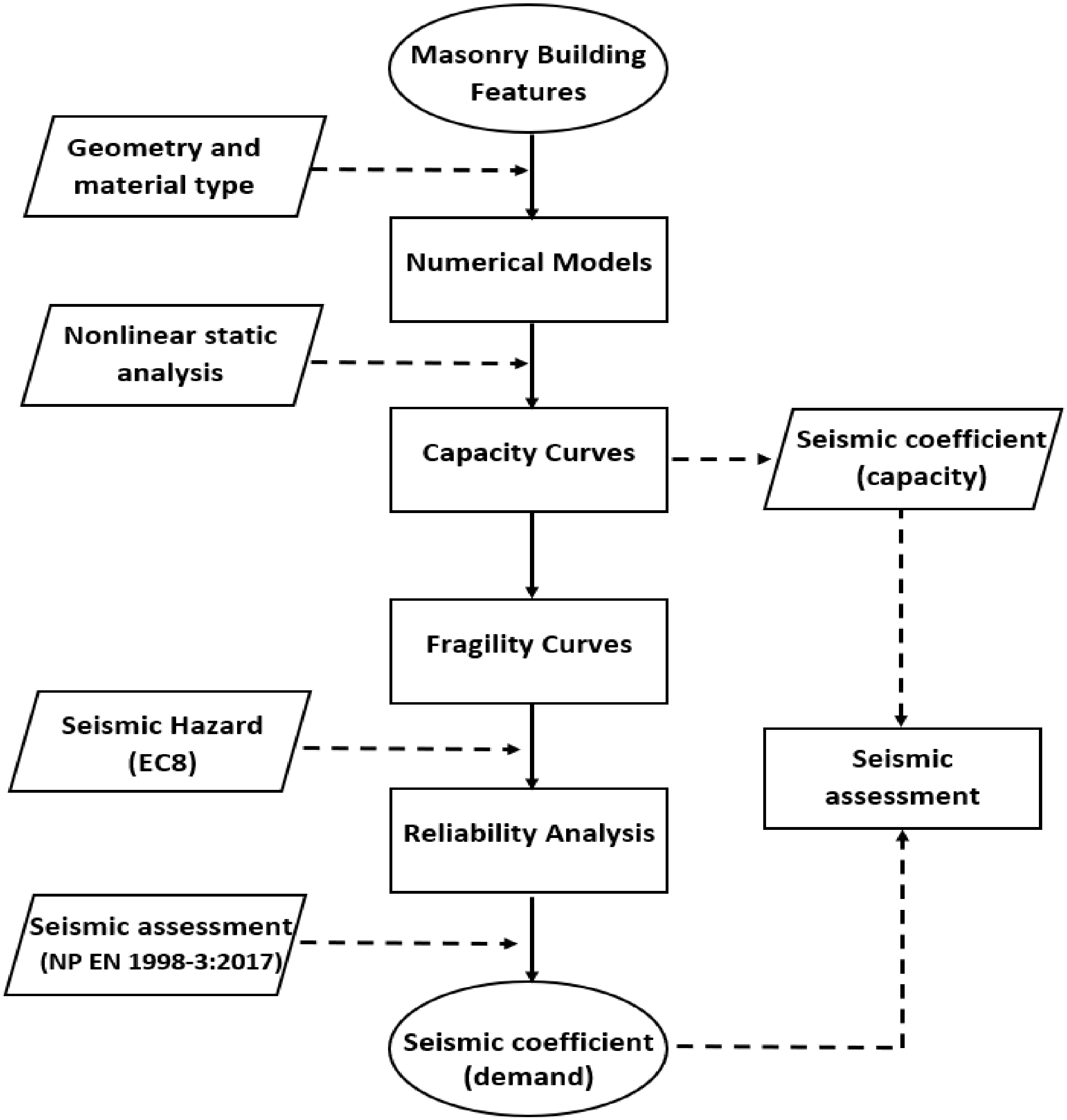
4. **Rapid methods for seismic assessment**
    - The proposed methodologies are divided in two levels and depend on the evaluated parameter: ratio between the walls area and floor area (method I) or seismic coefficient (method II).

5. Calibration of propose methods

- The reliability index to be required is adjusted considering the number of structures that verify the safety or not in terms of deformation, for the significant damage (SD) limit state and Tr=308 years, according to Eurocode for a global nonlinear analysis;

- The accordance between the simplified methods (method I and II) and the reference method or method III (Eurocode) is assessed by confidence tests, to verify if the propose methodologies are conservative or not;

Main steps for the development of Rapid methods



Summary

Procedures to develop Rapid methodologies for seismic assessment of masonry buildings

Requirements for Rapid assessment method

Method	Structural model	Evaluate parameter	Requirements
III (Reference EC8)	Global nonlinear analysis	Global analysis: top displacement for 80% of maximum base shear	Geometry Wall thickness Material properties Self-weight
	Linear analysis	Local analysis: maximum strength (flexure and/or shear)	
II	Not necessary	Seismic coefficient	Geometry Wall thickness Material properties Self-weight
I	Not necessary	Ratio between the walls area and floor area	Geometry Wall thickness ~~Material properties~~ ~~Self-weight~~

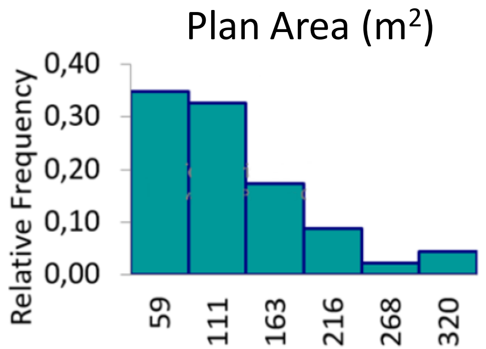
More conservative

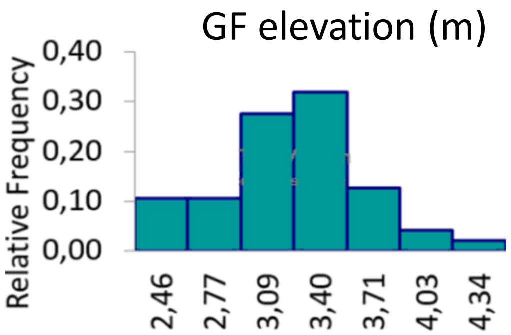
Overview behind the methodology

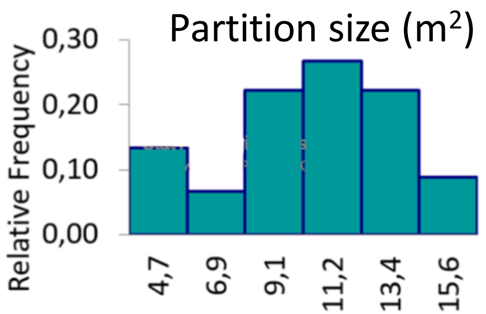
Geometry, materials and modelling

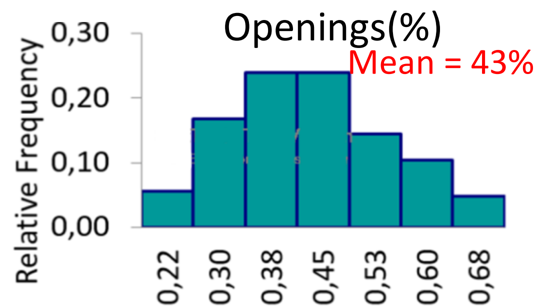
➢ Geometric characterization to define the representative buildings:

- Number of floors;
- Plan dimensions and elevation;
- Number of partitions;
- Wall thickness;
- Percentage of openings;
- Spandrels and piers dimensions;
- Slab thickness;
- Constructive and design details (materials, foundations, loads…)







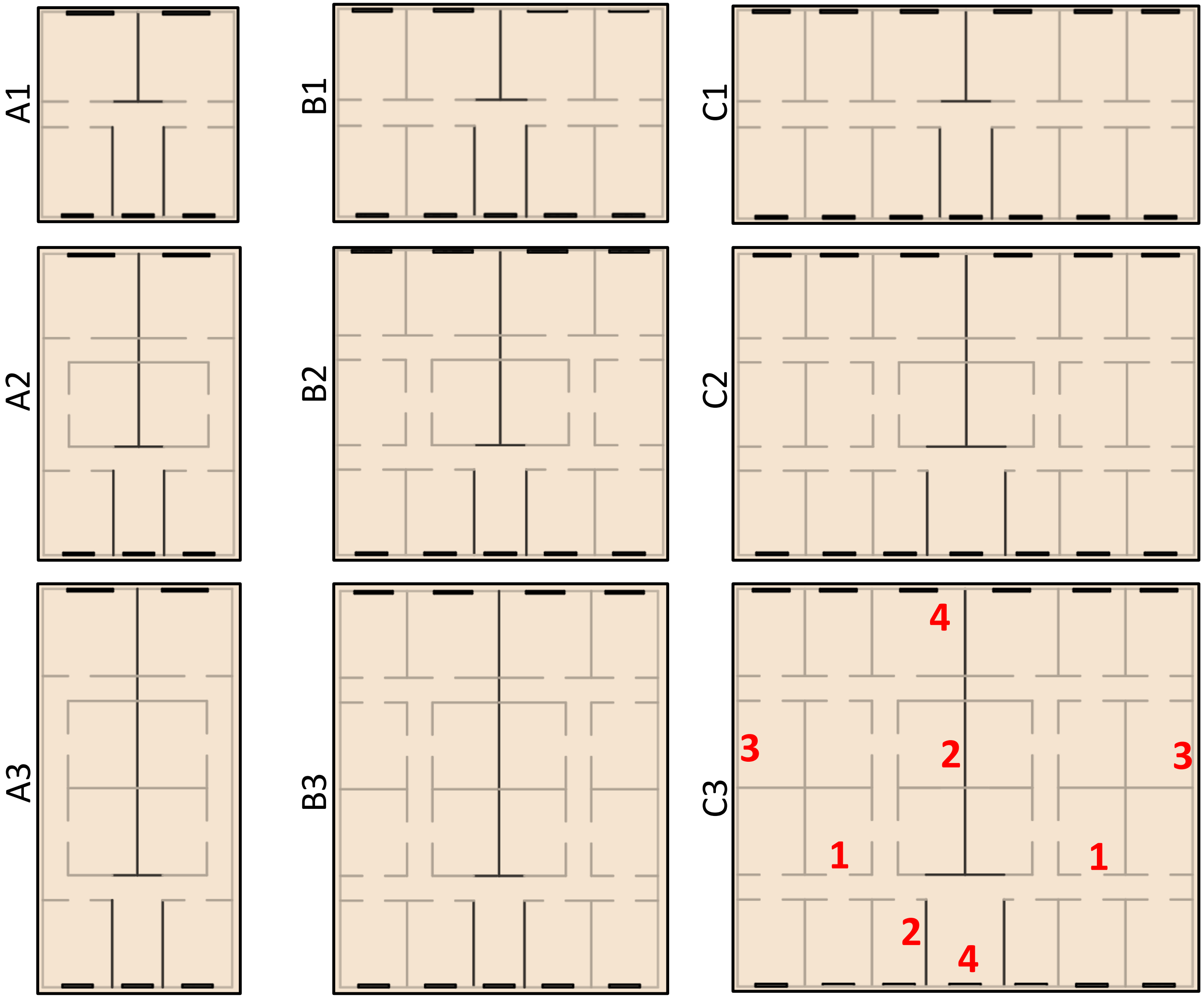


Mean wall thickness(m)

Wall	Floor			
	1	2	3	4 and 5
Partition	0,11	0,11	0,11	0,11
Interior	0,20	0,21	0,20	0,20
Common	0,32	0,31	0,29	0,29
Facade	0,48	0,47	0,42	0,42

Geometry, materials and modelling

- Defined **9 plans** to represent the building stock geometry



Type	Size (m)	Area (m^2)
A1	7.5x8.0	60.0
A2	7.5x12.5	93.8
A3	7.5x16.0	120.0
B1	12.5x8.0	100.0
B2	12.5x12.5	156.3
B3	12.5x16.0	200.0
C1	17.5x8.0	140.0
C2	17.5x12.5	218.8
C3	17.5x16.0	280

1 – Partition walls
2 – Interior walls
3 – Side walls
4 – Facade walls

Geometry, materials and modelling

- Analysis of uncertainty in masonry properties - ***E, G, ϒ,*** f_c***, c, μ.***
  - *Monte Carlo* simulation *(100 samples).*
  - Error ~ 5% for samples generated with a C.I. = 95%

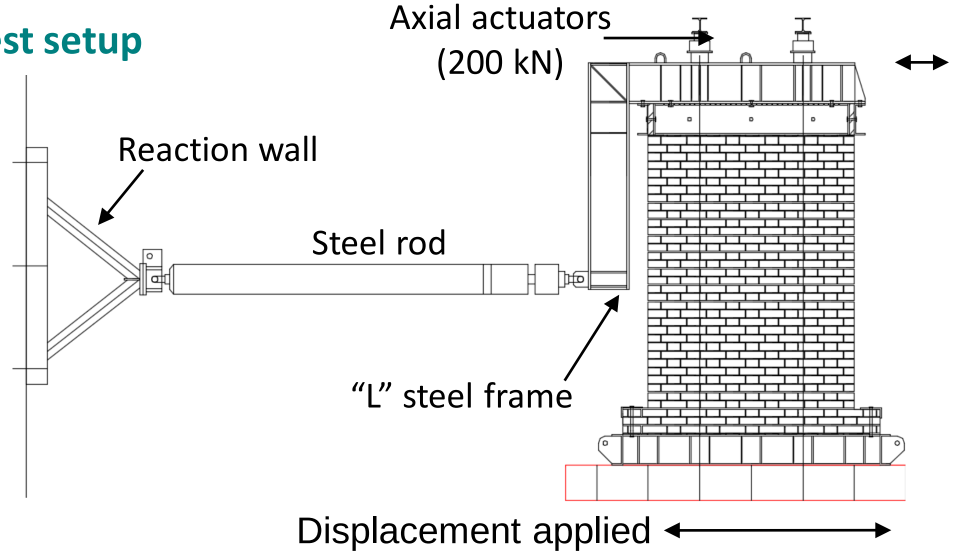
Correlated by **K** factor

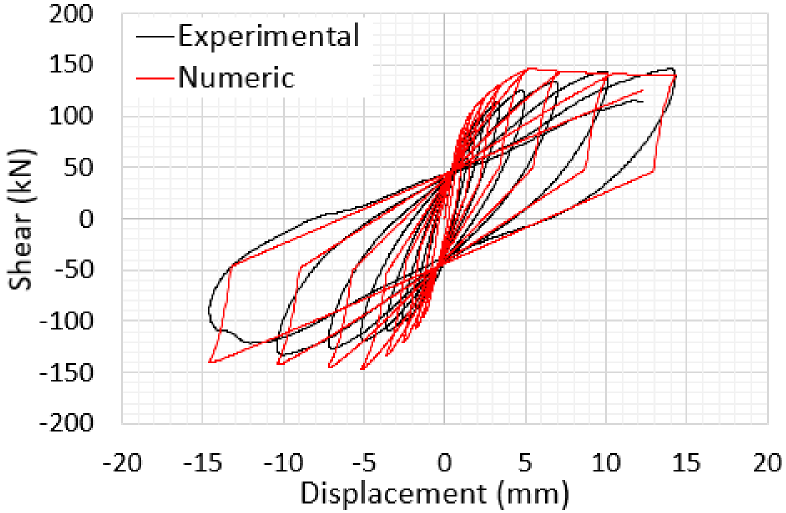
Variable	Masonry (solid clay bricks)		Masonry (hollow clay bricks)		Distribution
	mean	COV	mean	COV	
E [GPa]	4,50	0,25	1,50	0,25	LogNormal
G [GPa]	1,80	0,29	0,65	0,29	LogNormal
ϒ [kN/m³]	18,0	0,05	12,0	0,05	Normal
Factor K [-]	800 (250 - 1100)	0,25	700 (250 - 1100)	0,25	Truncated Normal
Fc [MPa]	5.40	0,17	2,10	0,17	LogNormal
c [MPa]	0,20	0,40	0,20	0,4	LogNormal
μ [-]	0,15	0,19	0,15	0,19	LogNormal

Geometry, materials and modelling

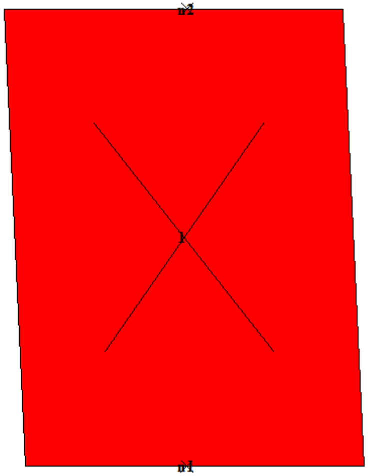
➢ Calibration and validation of macroelement on Tremuri with cyclic experimental test:

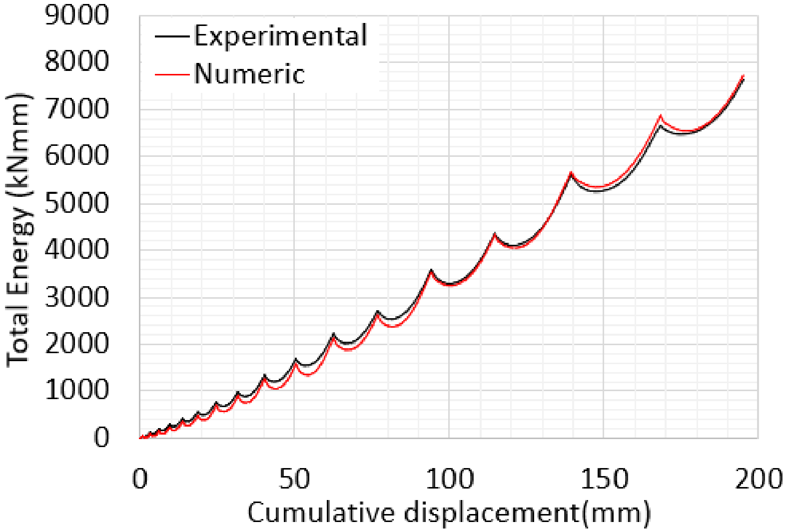
Test setup





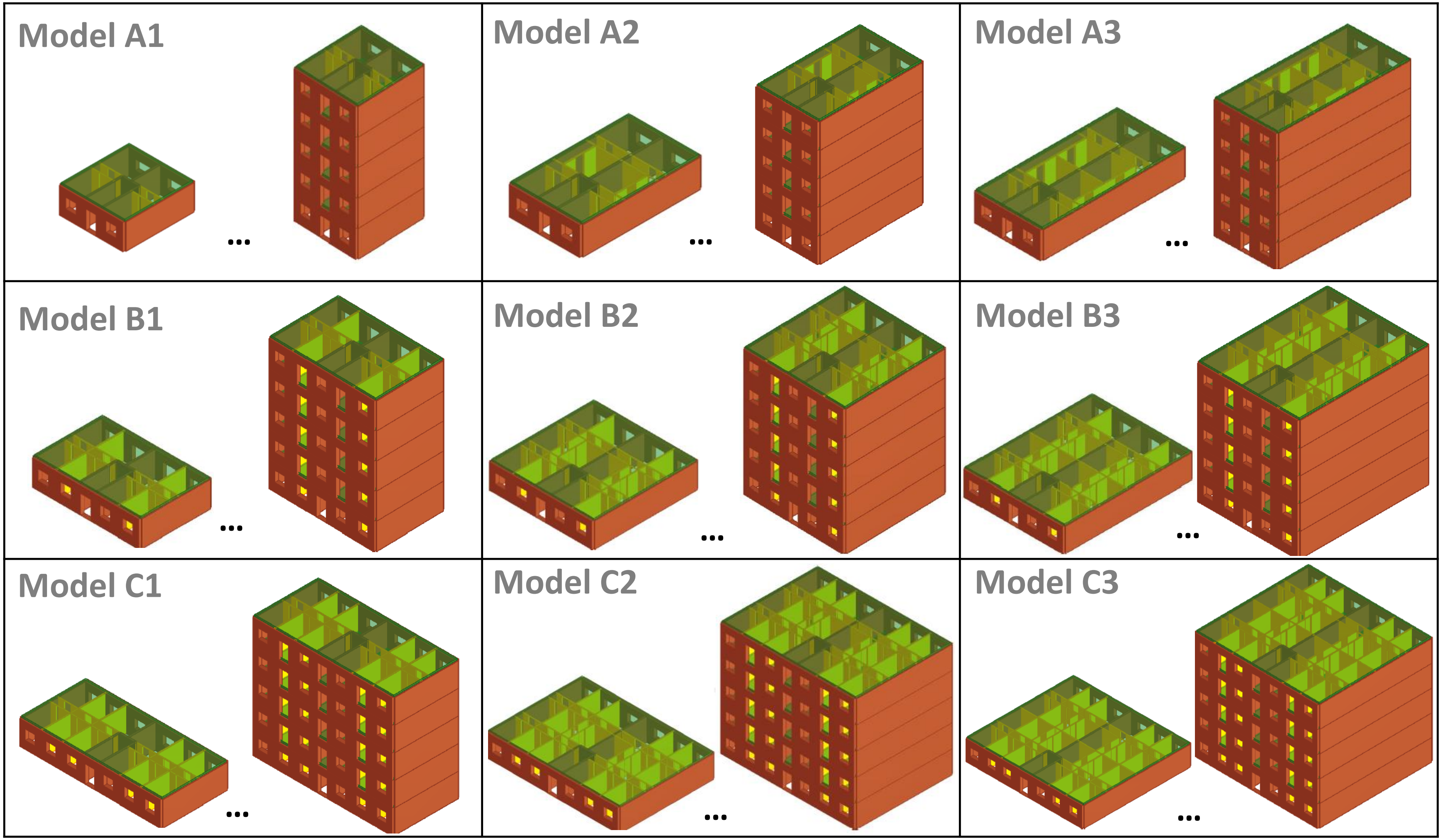
Damage pattern



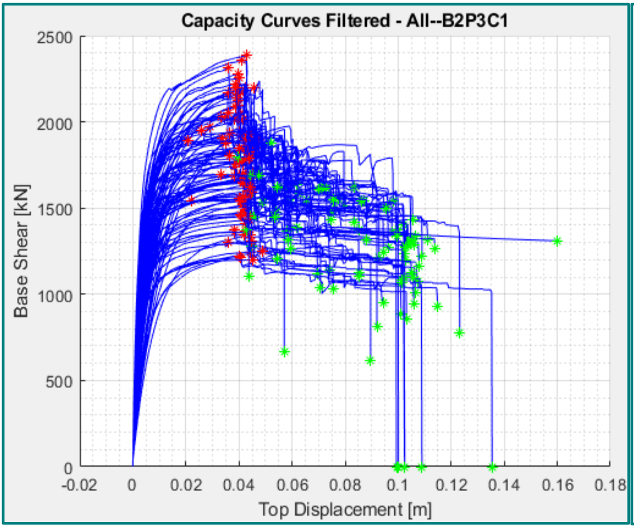


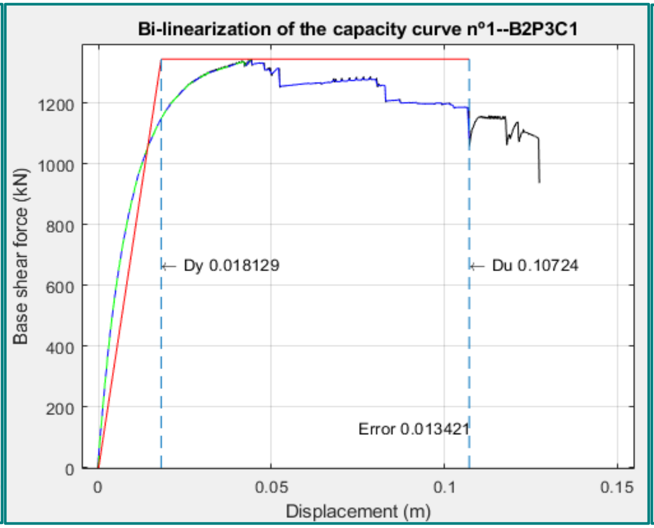
Geometry, materials and modelling

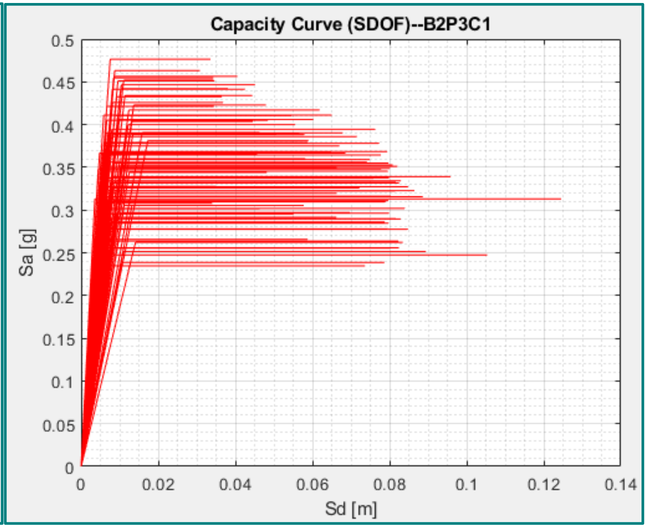
Built **45 numerical models** (9 plans x 1 to 5 floors) to represent the building stock.

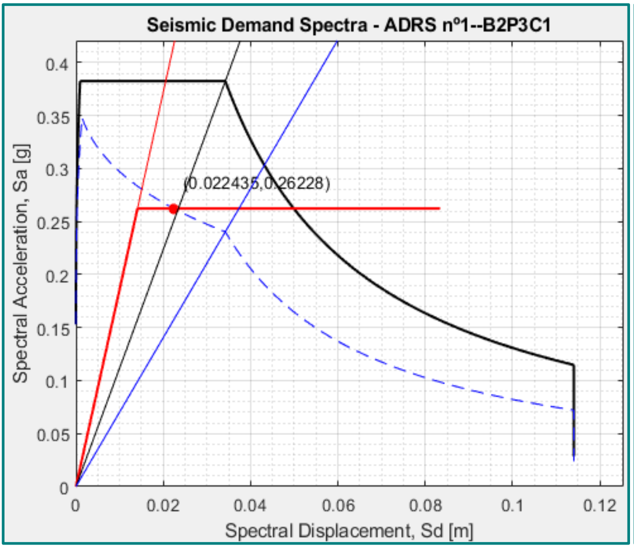


Step 1: Performance point for a given seismic action

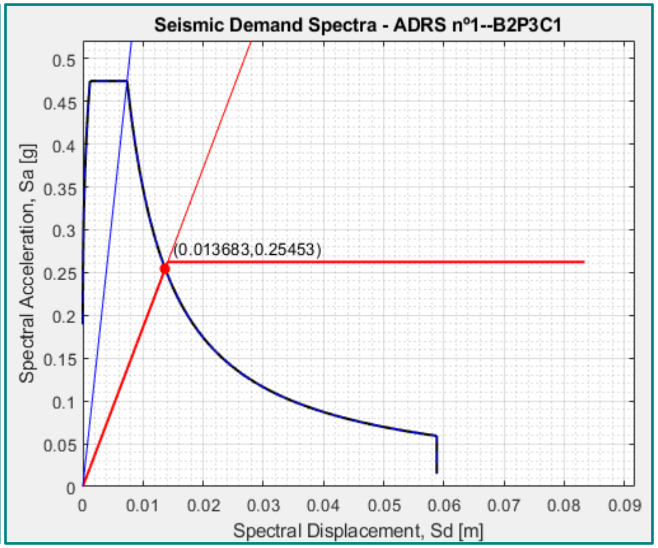








Lisbon (1.3), soil B, Tr=308



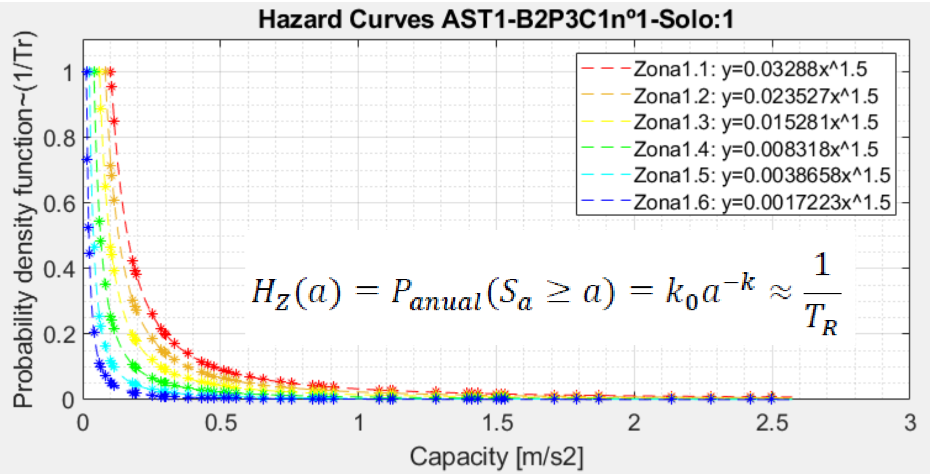
Lisbon (2.3), soil B, Tr=308

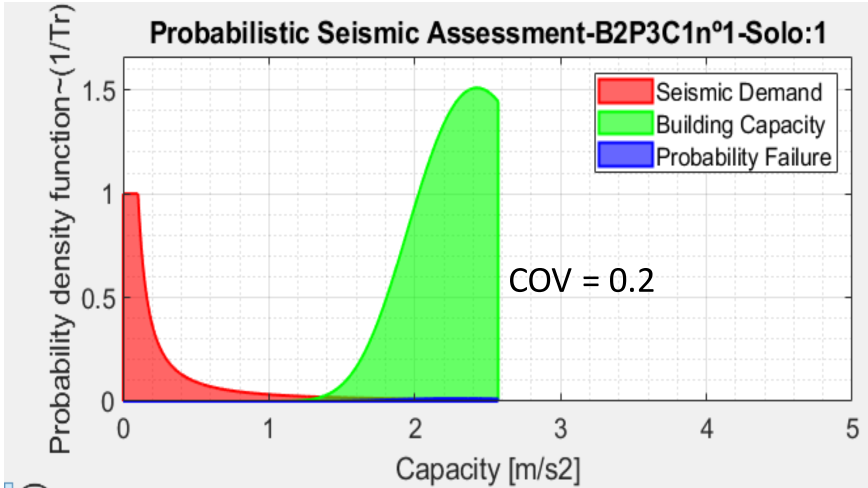
Remarks:

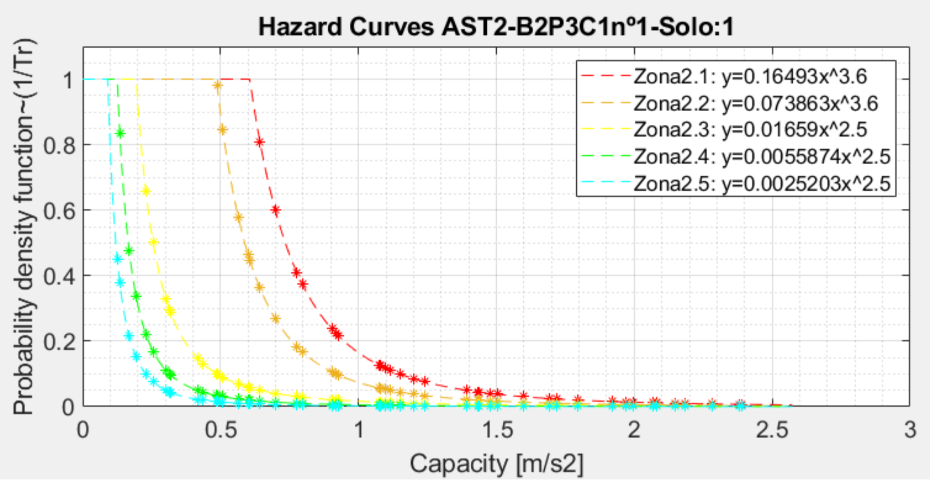
Bilinearization:
NP EN 1998-3:2017 (Annex C)

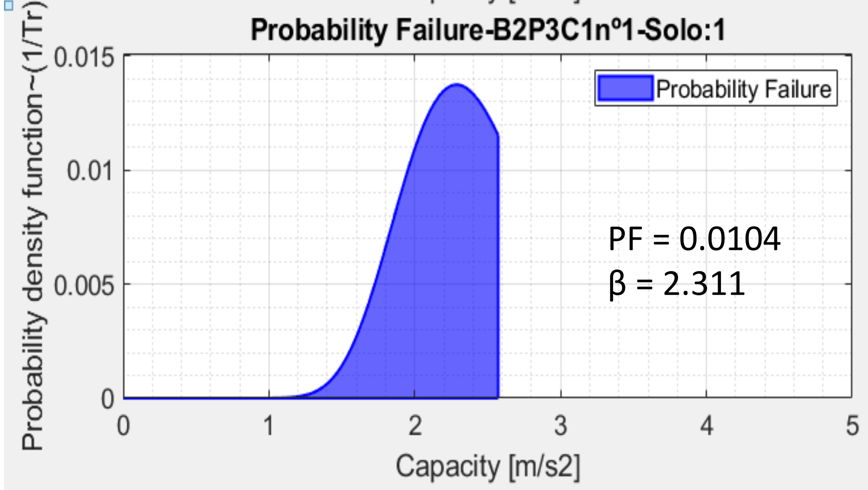
Performance point:
NP EN 1998-1:2010 (Annex B – B.5)

Step 2: Probabilistic seismic assessment and reliability

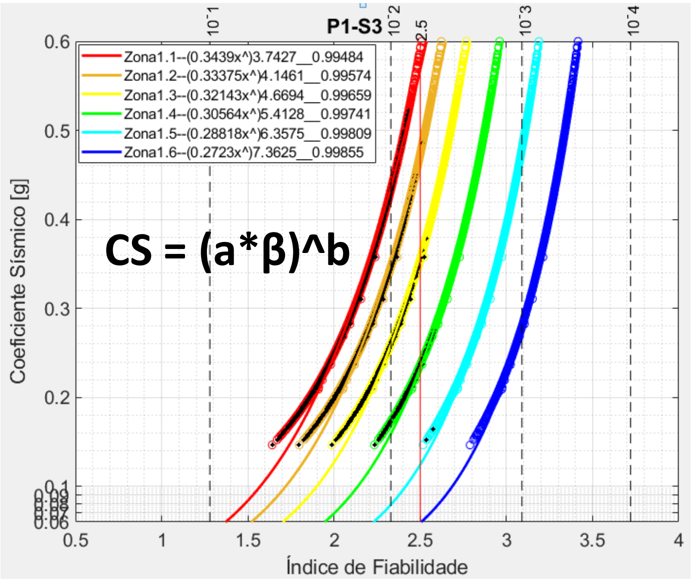


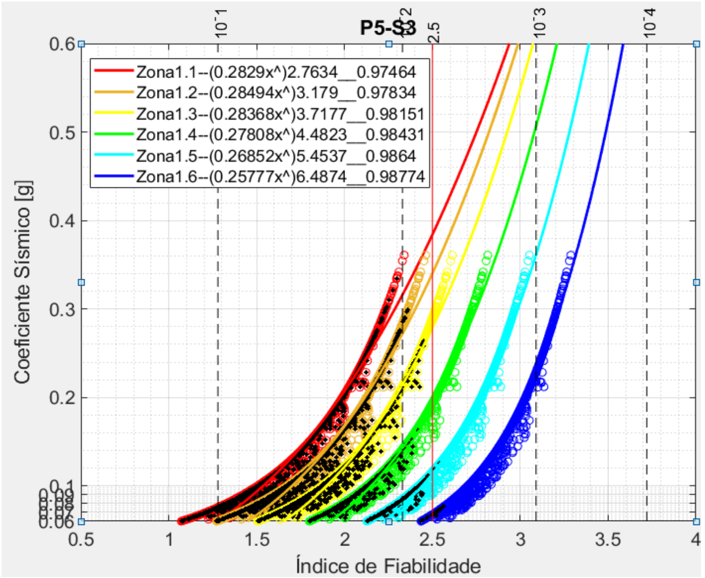


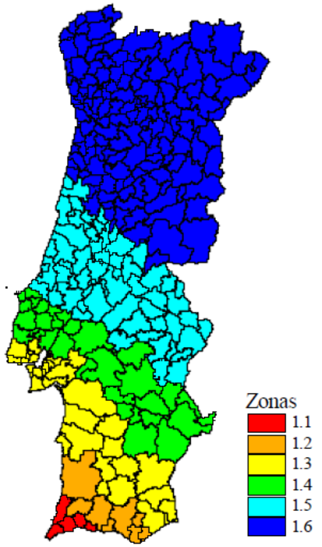


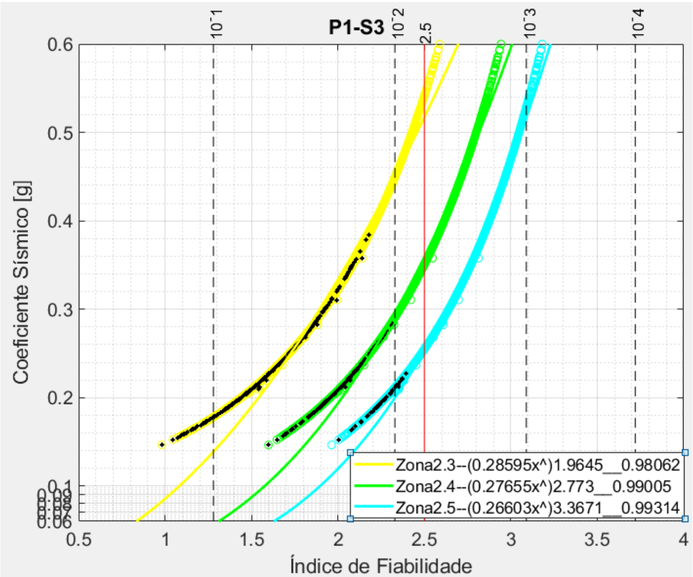


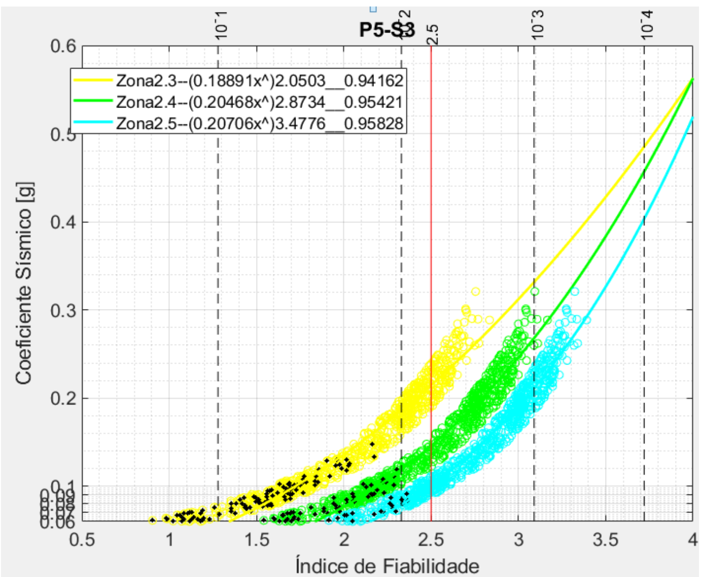
Step 3: Rapid methods for seismic assessment

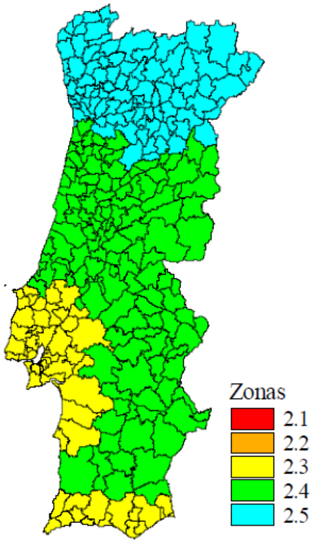












Step 4: Rapid methods and Calibration – method II

- Seismic coefficient to be compared to the demand, should be obtained using the following expressions:

$$V_{Rk} = \min\left\{V_{clk}, V_{cdk}, V_{flk}\right\}$$

Sliding:

$$V_{clk} = l_c \cdot t \cdot \left(f_{v0k} + \mu \cdot \sigma_0 \right)$$

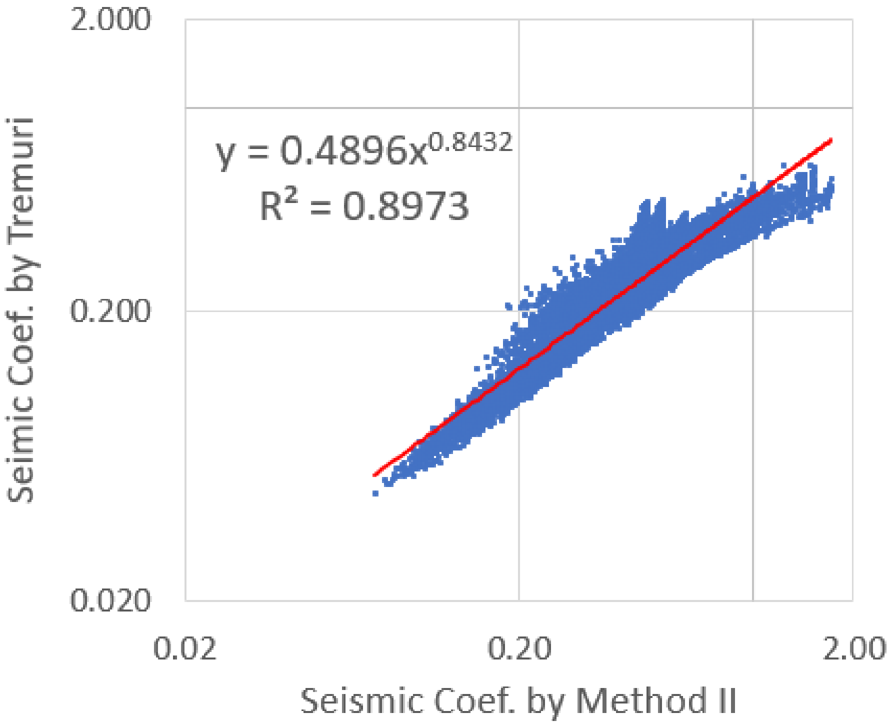
Diagonal shear:

$$V_{cdk} = A \cdot \frac{f_{tk}}{b} \cdot \sqrt{\frac{\sigma_0}{f_{tk}} + 1}$$

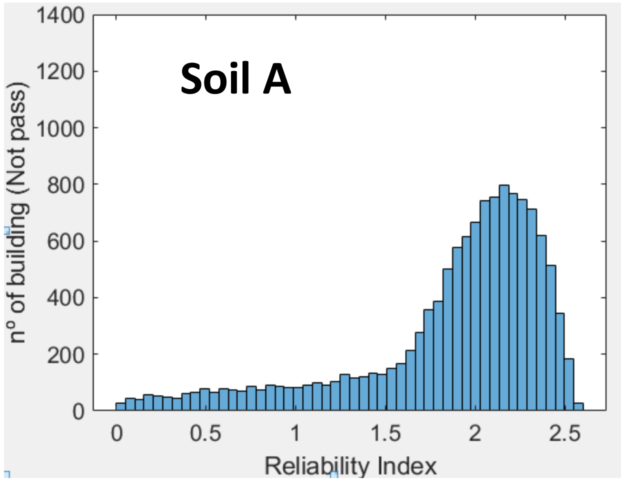
Flexure:

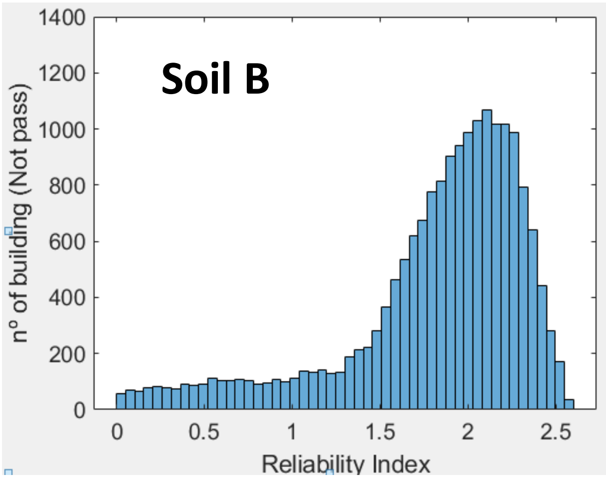
$$V_{flk} = \frac{\dfrac{\sigma_0 \cdot t \cdot l^2}{2} \cdot \left(1 - \dfrac{\sigma_0}{k \cdot f_k}\right)}{\alpha \cdot h}$$

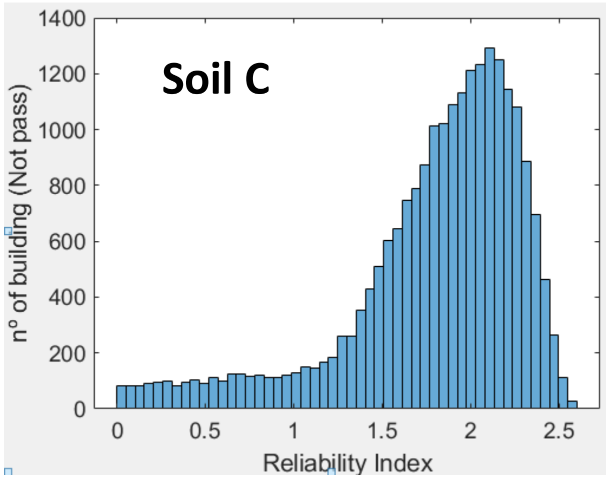
Seismic coefficient correction for nonlinear effects



Step 4: Rapid methods and Calibration – method II







Required Seismic Coefficient for β = 2.5 (uniform reliability index)

Seismic Zone	1 piso			2 piso			3 piso			4 piso			5 piso		
	Solo A	Solo B	Solo C	Solo A	Solo B	Solo C	Solo A	Solo B	Solo C	Solo A	Solo B	Solo C	Solo A	Solo B	Solo C
1.1	0.359	0.416	0.450	0.328	0.365	0.398	0.303	0.341	0.378	0.280	0.327	0.360	0.266	0.316	0.339
1.2	0.284	0.354	0.398	0.262	0.323	0.352	0.252	0.297	0.326	0.239	0.279	0.312	0.225	0.268	0.303
1.3	0.213	0.274	0.320	0.193	0.253	0.297	0.187	0.245	0.278	0.184	0.232	0.258	0.180	0.219	0.245
1.4	0.130	0.185	0.226	0.120	0.172	0.205	0.117	0.166	0.200	0.117	0.164	0.196	0.116	0.162	0.191
1.5	0.054	0.096	0.120	0.059	0.096	0.115	0.064	0.093	0.112	0.066	0.092	0.111	0.066	0.091	0.111
1.6	0.096	0.043	0.047	0.041	0.039	0.052	0.030	0.041	0.056	0.027	0.045	0.060	0.028	0.048	0.061
2.1	0.517	0.572	0.618	0.433	0.483	0.513	0.350	0.389	0.408	0.278	0.311	0.331	0.229	0.255	0.270
2.2	0.456	0.519	0.556	0.388	0.437	0.469	0.311	0.351	0.378	0.242	0.279	0.302	0.197	0.228	0.248
2.3	0.342	0.431	0.481	0.308	0.375	0.411	0.243	0.296	0.327	0.181	0.227	0.254	0.143	0.182	0.206
2.4	0.207	0.293	0.350	0.194	0.268	0.315	0.153	0.211	0.248	0.109	0.155	0.185	0.084	0.121	0.147
2.5	0.138	0.201	0.249	0.128	0.190	0.230	0.106	0.150	0.182	0.083	0.108	0.132	0.068	0.084	0.103

Step 4: Rapid methods and Calibration – method II

	Method II					
Seismic Zone	**Match**	**Not Match**	**False Positives**	**False Negatives**	**FalseNegatives Global**	**False Positives Global**
1.1	66.4%	33.6%	6.9%	93.1%	31.3%	2.3%
1.2	61.9%	38.1%	5.3%	94.7%	36.1%	2.0%
1.3	64.8%	35.2%	6.8%	93.2%	32.8%	2.4%
1.4	77.9%	22.1%	11.1%	88.9%	19.7%	2.5%
1.5	94.2%	5.8%	39.1%	60.9%	3.5%	2.3%
1.6	99.7%	0.3%	98.8%	1.2%	0.0%	0.3%
2.1	34.8%	65.2%	0.0%	100.0%	65.1%	0.0%
2.2	33.2%	66.8%	0.0%	100.0%	66.7%	0.0%
2.3	42.0%	58.0%	0.1%	99.9%	58.0%	0.1%
2.4	65.6%	34.4%	0.7%	99.3%	34.2%	0.2%
2.5	86.5%	13.5%	3.3%	96.7%	13.0%	0.4%
					32.8%	**1.1%**

33.90%

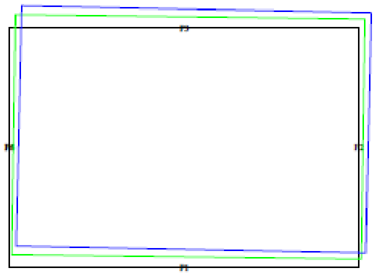
Assessment		
EC8	**Method II**	**Status**
✓	✓	Match
✗	✗	Match
✗	✓	Not Match (F.P.) – not conservative
✓	✗	Not Match (F.N.) – conservative

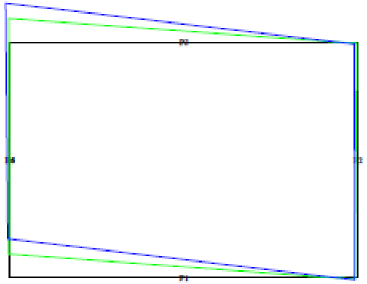
297/27000

buildings

Final comments

- 9000 buildings were analyzed in different soils and seismic zones (27000 in total);
- Out-of-plane mechanisms are not considered in this version;
- The Rapid methods are valid for soils A, B and C; importance class II; regular geometry and up to 5 stories height;
- The method is valid for building aggregates;
- The assertiveness of the method II is around 34%, where 33% of the cases are false negatives;
- Method I was not presented but is more conservative and requires only the thickness of the primary walls. The demand will be expressed in terms of allowable tension or walls area in the seismic action direction;
- Extend the methodologies for flexible diaphragms.





THANK YOU