Contribution to Seismic Safety & Risk Assessment of Pre-Code Masonry Buildings

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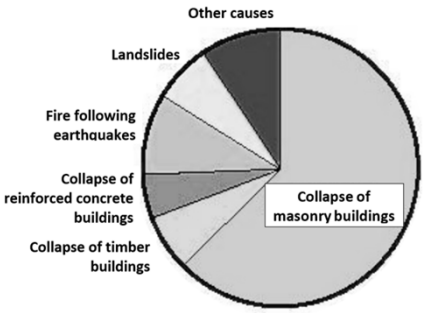
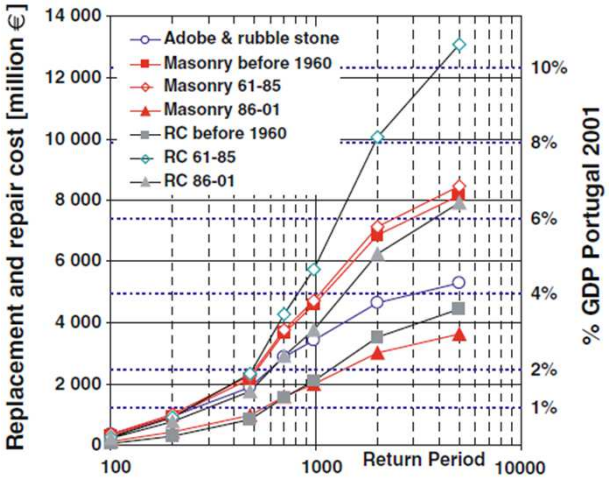
I – Motivation and research objectives

- The major number of collapses caused by earthquake events occur in masonry buildings;
- 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.



Coburn & Spence, 2002

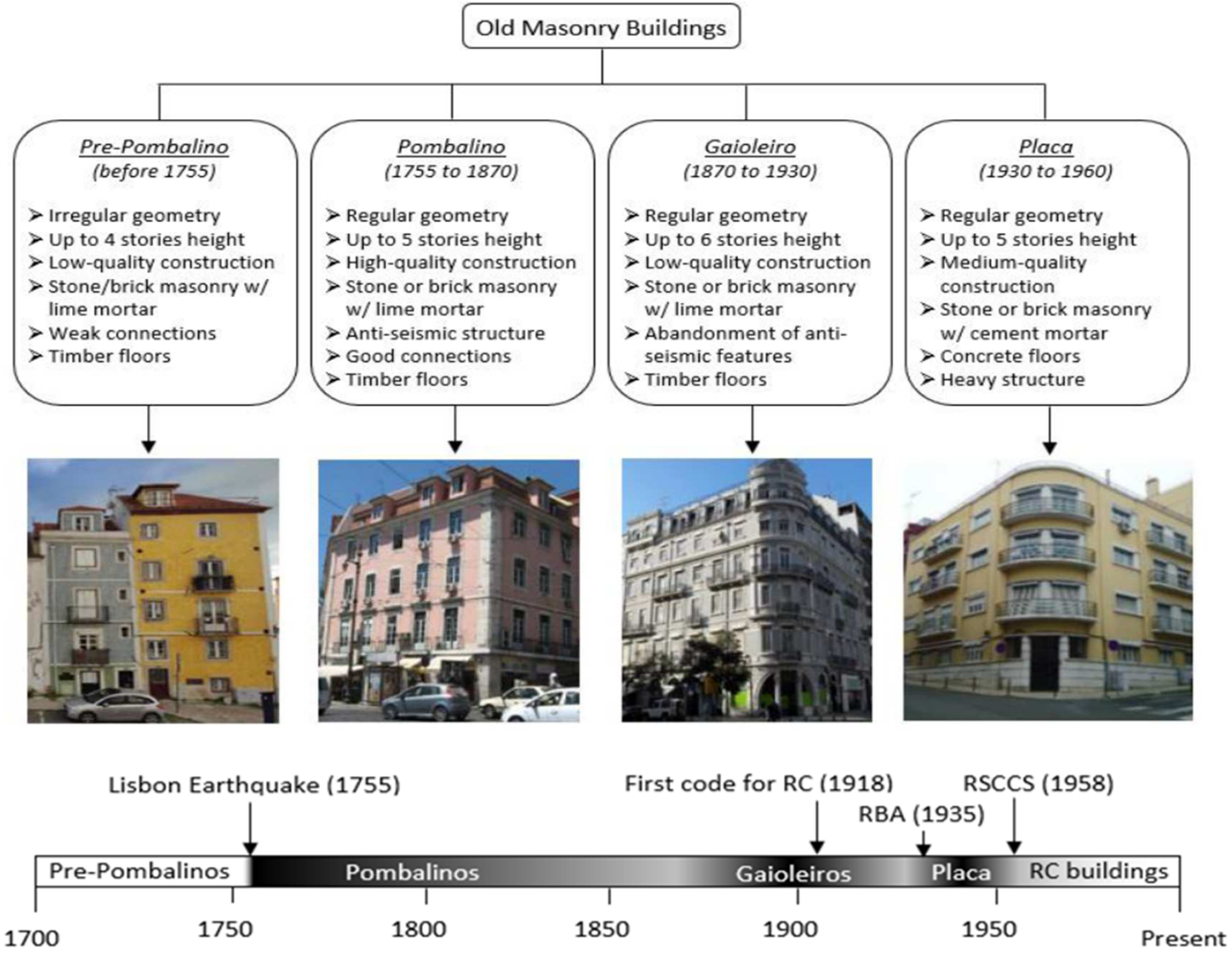


Campos Costa et. al. 2010

Main goals:

- Contribution for the seismic safety of existing masonry buildings through the development of (expeditious) methods for seismic assessment;
- Provide seismic fragility curves to be used in seismic risk/loss studies and define seismic risk mitigation strategies, based in loss-effectiveness analysis.

II – Pre-code masonry buildings: Introduction



Overview of the work done

1. Conducting a Pilot Study on the Seismic Vulnerability Assessment of a Masonry Building Aggregate in Lisbon

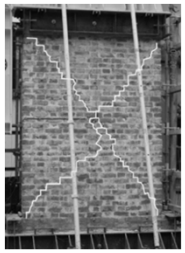
Summary and main topics

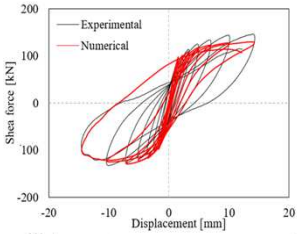
- Exploits the seismic vulnerability assessment of a pre-code masonry building ("Placa" typology) enclosed in aggregate;
- Comparison of two modelling strategies: Applied Element Method (in-plane and out-of-plane mechanisms) and an Equivalent Frame Modelling (only in-plane mechanisms);
- Numerical model validation based on experimental cyclic tests performed (Ana Marques, PhD Thesis);
- Ambient vibration tests on the full aggregate for numerical model calibration;
- Comparison of the influence of the aggregate in the seismic behavior;
- Seismic performance based on nonlinear static analyses and CSM;
- Site-specific ground motion simulated using a non-stationary stochastic model that takes into account the finite fault effects (*Alexandra Carvalho, PhD Thesis*);
- Derive seismic fragility curves considering the variability in the seismic demand;

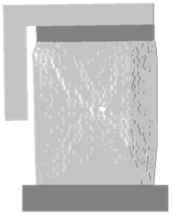
Building's description, experimental tests and numerical modelling

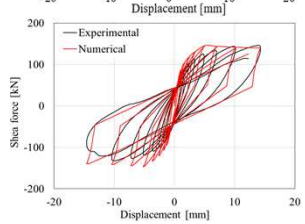
Case study

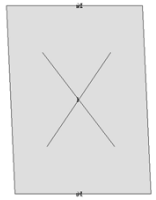
Numerical modeling calibration and validation



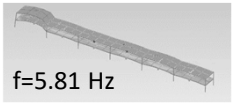


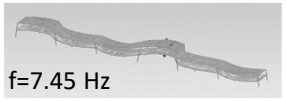


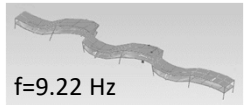




Experimental

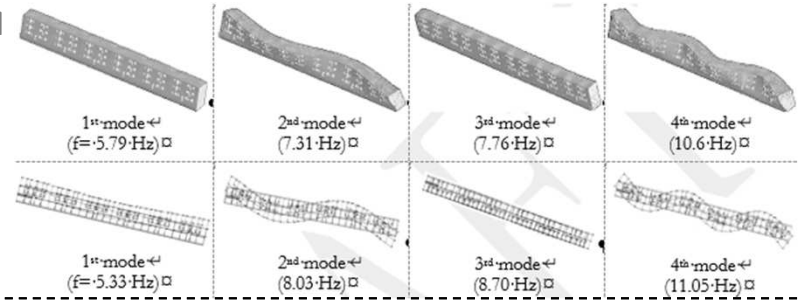




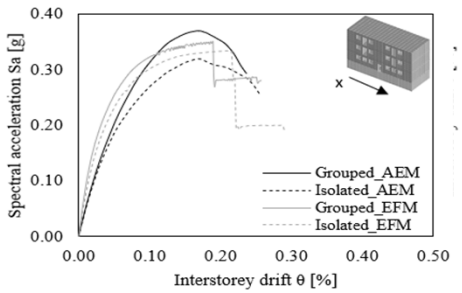


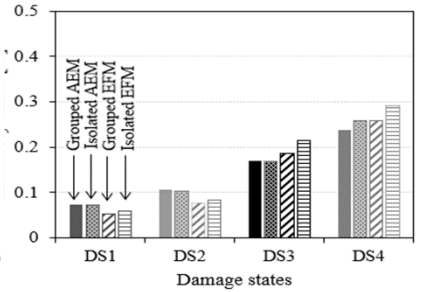
AEM

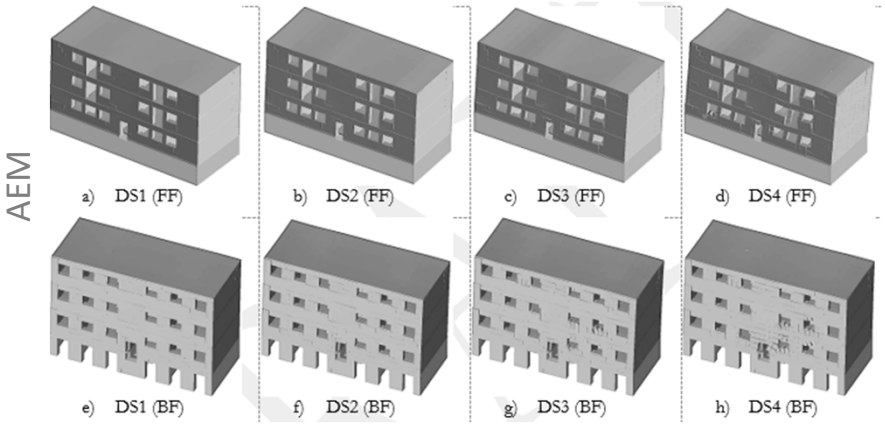
EFM

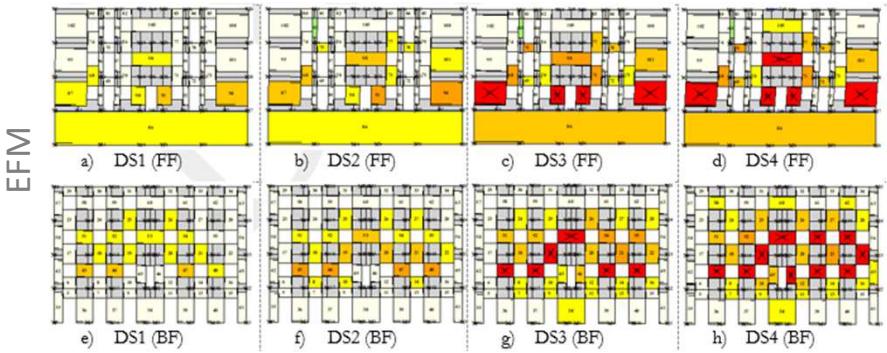


Numerical analyses and failure mechanisms (direction XX)



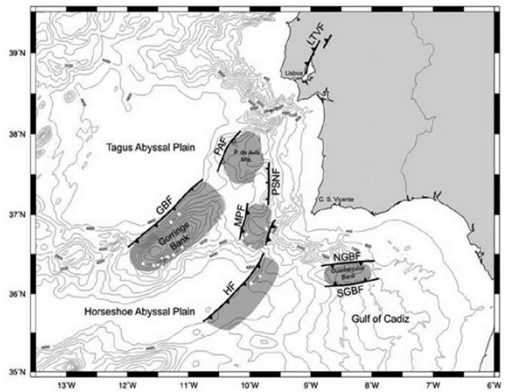


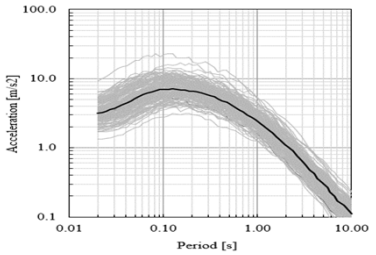


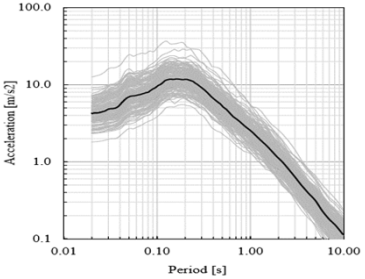


Seismic performance-based assessment and fragility curves

Seismic action (bedrock and at ground surface)



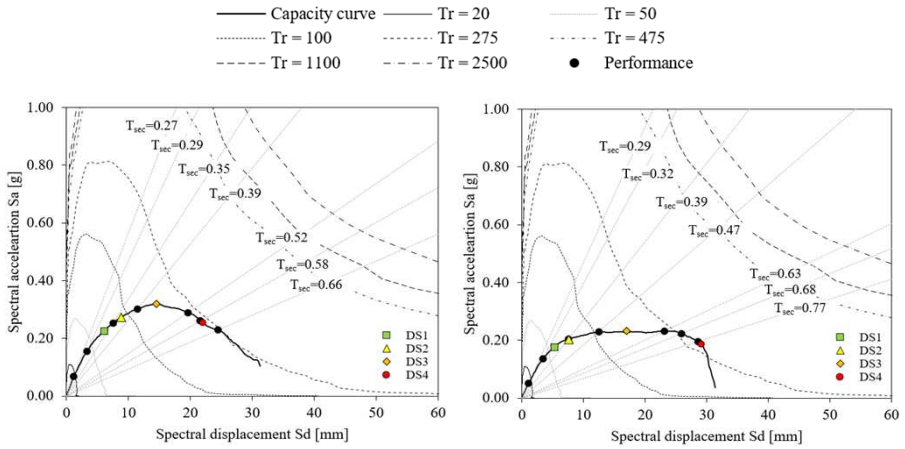




Onshore (LTVF): Mw= 4.8, 5.3, 5.8, 6.1, 6.6, 6.8, 7.1

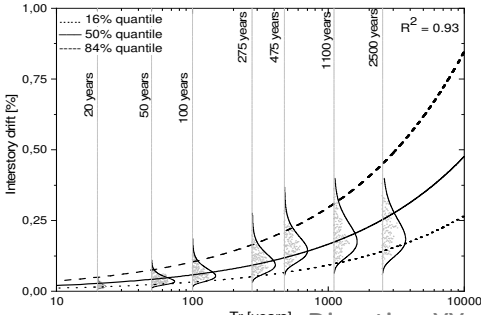
Offshore (HS): Mw= 7.2, 7.5, 7.9, 8.2, 8.4, 8.5, 8.8

Seismic performance at bedrock (LTVF)

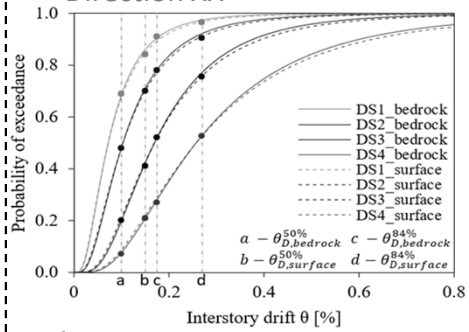


Seismic fragility curves (LTVF)

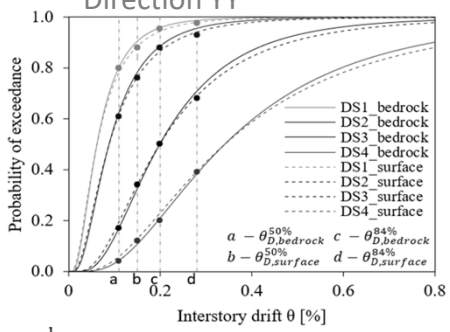
150 simulations for each magnitude, scenario and ground

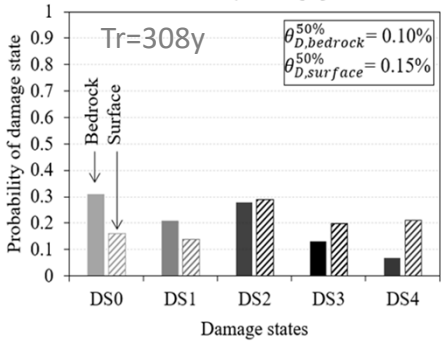


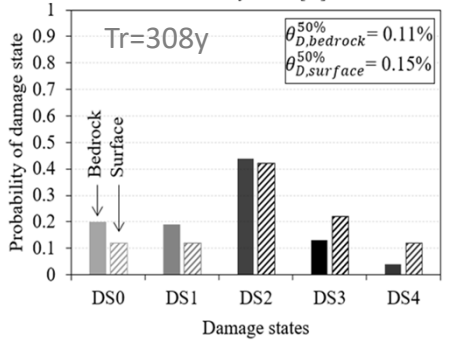
Direction XX



Direction YY







Minor damage: 14% (X) and 12% (Y); Severe: 20% (X) and 22% (Y);
Moderate: 29% (X) and 42% (Y); Extensive: 21% (X) and 12% (Y)

Overview of the work done

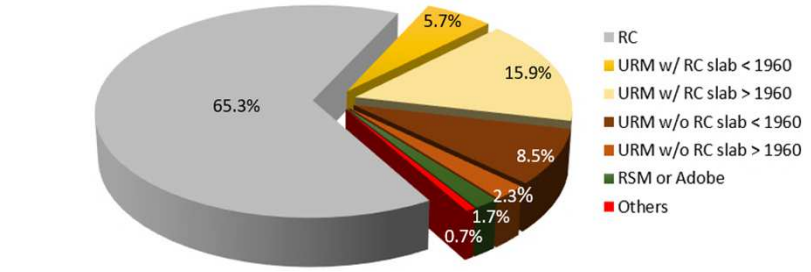
2. Geometric Characterization of Old Masonry Buildings for Seismic Risk Assessment in Lisbon

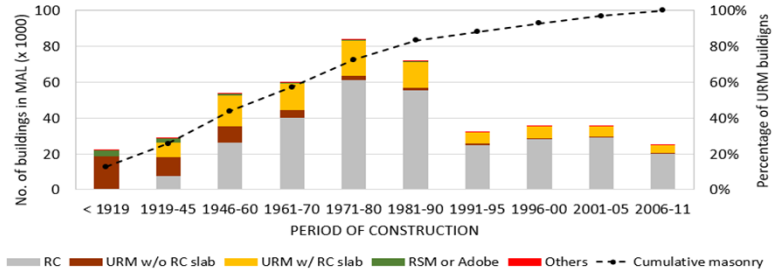
Summary and main topics

- Geometry characterization of pre-code masonry buildings (up to 1960) based on a comprehensive and exhaustive survey;
- The number of buildings surveyed was randomly selected for a population of 100 masonry buildings (around 10%, 24%, 27%, 29% and 10% for 1 to 5 stories height, respectively);
- The geometrical characterization was based on the following parameters collected: plan dimensions, elevation, stories height, number of partitions, hall dimensions, walls thickness (facade, interior, partition and lateral side walls), openings dimension, interior walls length and type/thickness of floors (RC and timber);
- The distribution of the parameters collected was represented by histograms. For some parameters, a probability density functions were fitted to the data and evaluated using K-S tests;
- The information collected and the statistics presented are of paramount importance to characterize the building stock and to generate a large sound database;

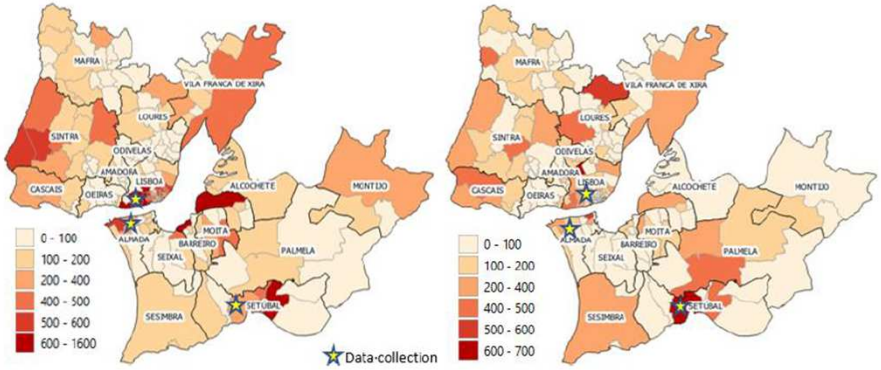
Geometric data collection in MAL

Overview of the building stock in MAL





Pre code masonry buildings distribution (census 2011)

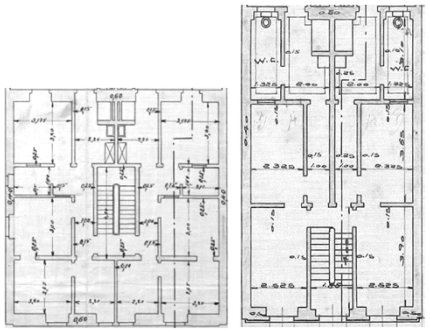


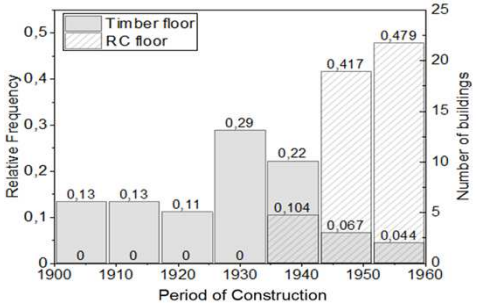
URM w/o RC slabs

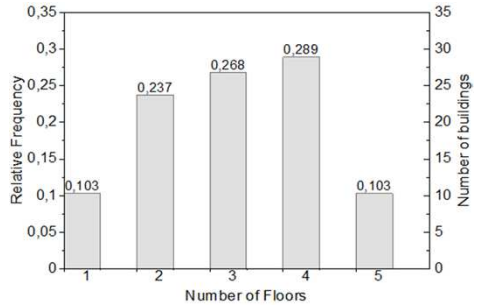
URM w/ RC slabs

Geometric parameters collected

Legend/Parameter	Plan view	Facade view
Plan dimensions – L_x and L_y		
Building height		
Stories height		
Number of partitions (1)		
Hall dimension (2)		
Wall thickness: facades (3); interior (4), partition (5), side walls (6)		
Openings dimensions (7)		
Interior walls length		
Floor (type and thickness)		

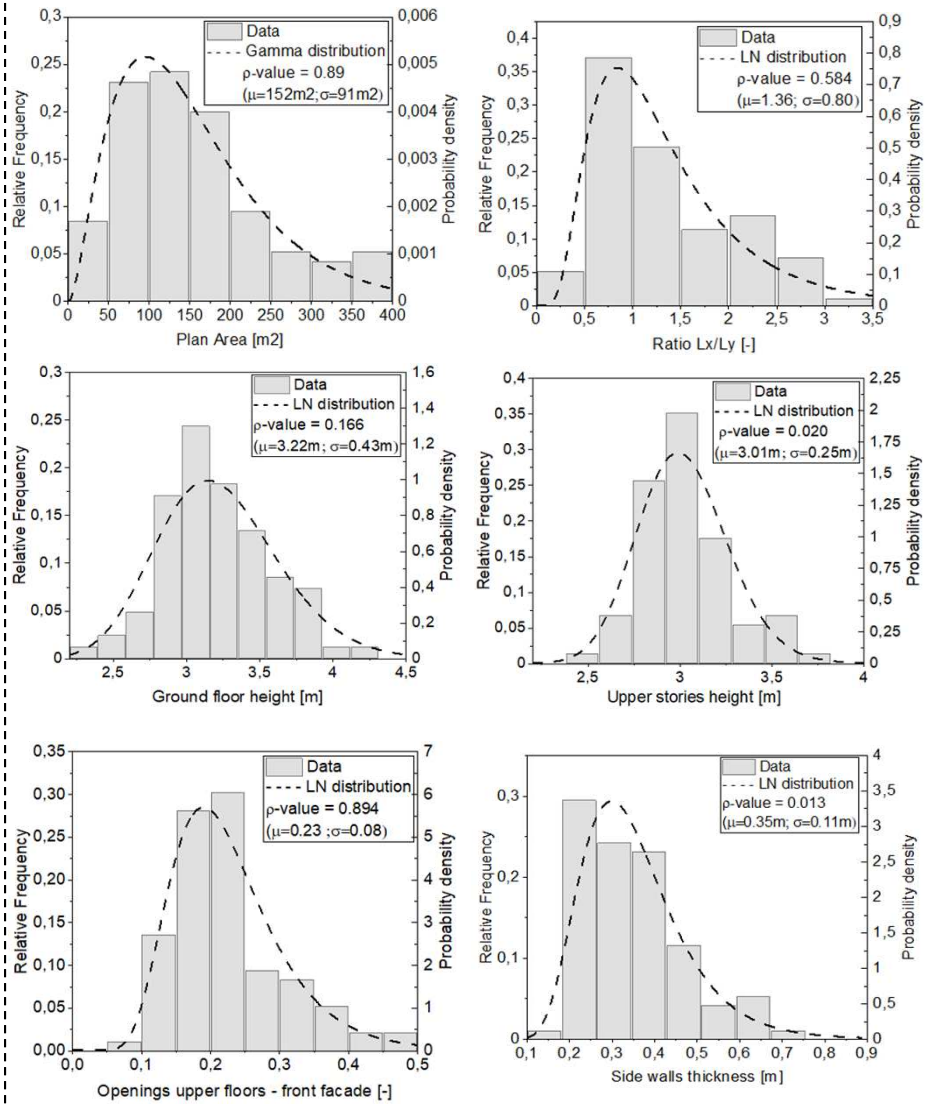






Geometric parameters collected and statistical properties

Example of the histograms and analytical distributions fitted



Summary of the statistical properties

Parameter	Unit	Distribution	Mean	C.O.V.	Mode	1st quartile	Median	3rd quartile
Length Lx	m	LogNormal	12.6	0.40	-	7.3	12.1	17.6
Length Ly	m	LogNormal	12.1	0.34	-	8.2	11.2	14.3
Plan area	m²	Gamma	151.6	0.60	-	82.6	130.3	197.0
Lx/Ly ratio	-	LogNormal	1.36	0.58	-	0.76	1.11	1.95
Ground floor height	m	LogNormal	3.23	0.13	-	2.96	3.20	3.50
Upper stories height	m	LogNormal	3.01	0.08	-	2.80	3.00	3.25
Opening ratio (ground floor)	-	LogNormal	0.26	0.38	-	0.20	0.23	0.27
Opening ratio (front facade)	-	LogNormal	0.23	0.35	-	0.17	0.21	0.26
Opening ratio (rear facade)	-	Normal	0.21	0.38	-	0.16	0.21	0.25
Interior walls density	-	Normal	0.054	0.19	-	0.047	0.055	0.061
Compartments Area	m²	Normal	13.7	0.22	-	11.6	13.95	15.59
Wall thickness (Facade)	m	LogNormal	0.47	0.30	-	0.40	0.50	0.60
Wall thickness (Side walls)	m	LogNormal	0.34	0.32		0.25	0.30	0.40
Wall thickness (partition)	m	-	0.14	0.15	0.15	0.13	0.15	0.15
Wall thickness (interior)	m	-	0.21	0.24	0.25	0.15	0.25	0.25
Average wall thickness reduction	m	-	0.11	0.51	0.10	0.10	0.10	0.10
Floor thickness (RC)	m	-	0.10	0.10	0.10	-	-	-
Floor thickness (timber)	m	-	0.20	0.05	0.20	-	-	-

Overview of the work done

3. Seismic Fragility Analysis and Vulnerability Assessment of Pre-Code Masonry Buildings

Summary and main topics

- Fragility functions are proposed for masonry buildings up to five stories high (with rigid and flexible floors) capacity and mechanistic vulnerability curves are derived for seismic assessment in compliance with EC8-3;

- The previous statistical information collected was used to derived representative archetypes of masonry buildings and to account the variability in the geometry;

- Two main classes of typologies were considered to account the variability in the material properties (Typology I - good quality masonry/ state of conservation; Typology II – poor quality masonry/state of conservation);

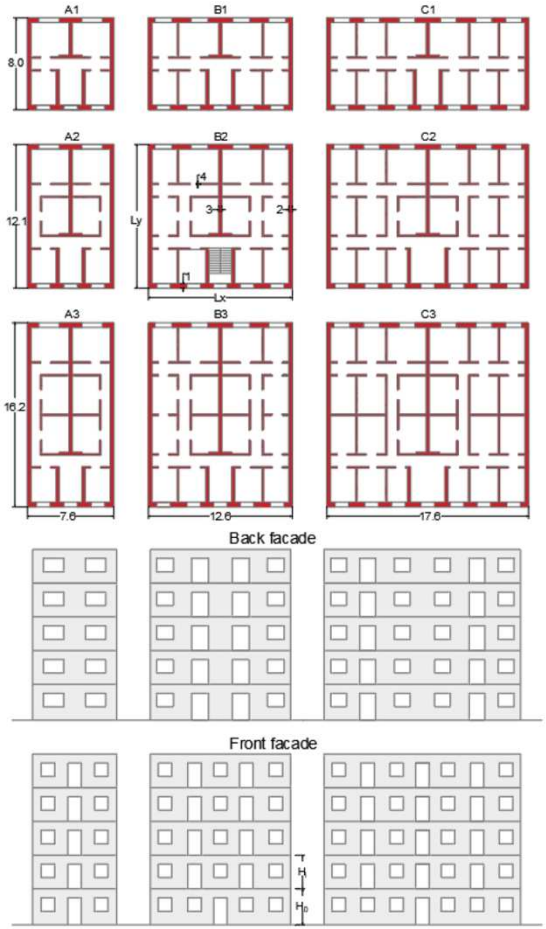
- A synthetic database of 18.000 buildings was generated to account the variability in geometry and materials;

- Tridimensional MDOF models were developed to simulate the nonlinear response of the buildings and nonlinear static analyses were performed (TreMuri Ricierca);

- Seismic action modelled for the entire country, through the elastic response spectrum defined in the National Annex of EC8 and a wide range of RP up to 5000 years;

Definition of the representative masonry building stock

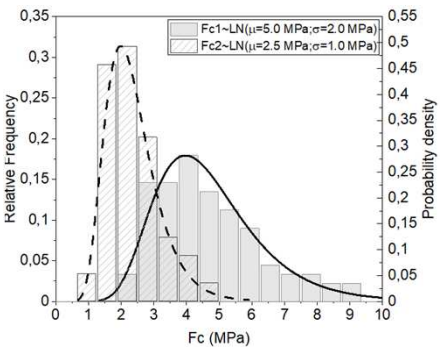
Definition of the representative archetypes - geometry

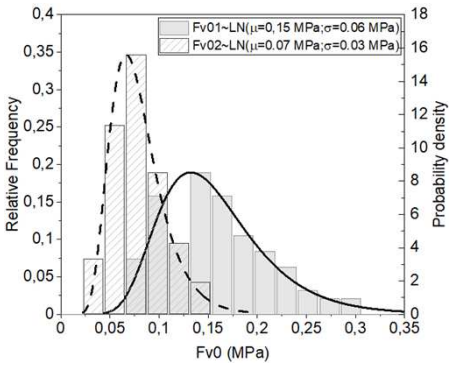


Moments	L_x [m]	L_y [m]	IWD [-]	H_0 [m]	H_i [m]	OR_F [-]	OR_B [-]	Th_1 [m]	Th_2 [m]	Th_3 [m]	Th_4 [m]	AWTR [-]
Mean	12.6	12.1	0.054	3.23	3.01	0.23	0.21	0.47	0.34	0.21	0.14	0.11
Std. deviation	5.00	4.1	0.01	0.42	0.24	0.08	0.08	0.14	0.11	0.05	0.02	0.06
Mode	-	-	-	-	-	-	-	-	-	0.25	0.15	0.10

L_x and L_y – length; H_0 and H_i – ground floor and upper floor interstorey heights; OR – openings ratio: front (OR_F) and back (OR_B) façade; IWD – interior walls density; Th – walls thickness: facades (1), side walls (2), interior walls (3), partition walls (4); AWR – average façade walls thickness reduction along the height.

Definition of the representative archetypes - materials

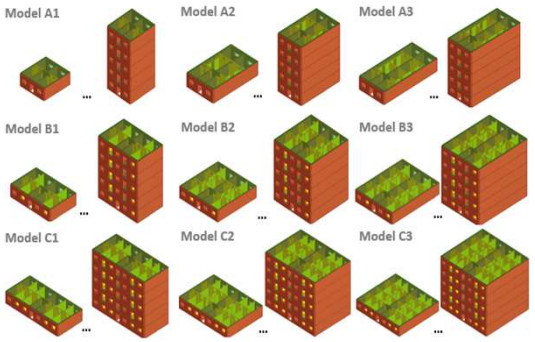


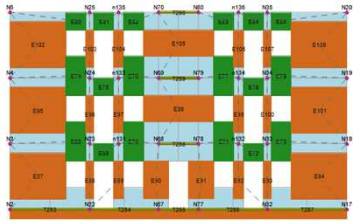


Random variable	Distribution	COV	Mean value			
			Type I-1	Type I-2	Type II-1	Type II-2
Compressive strength f_c [MPa]	LogNormal	0.40	5.00	2.00	2.50	1.25
Factor K* [-]	Truncated Normal	0.25	800 (250 - 1100)			
Young's modulus E [MPa]	-	-	4000	1600	2000	1000
Shear modulus G [MPa]	LogNormal	0.40	1700	650	850	450
Density ϱ [kg/m³]	Normal	0.10	1800	1200	1800	1200
Cohesion τ_0 [MPa]	LogNormal	0.40	0.15	0.15	0.07	0.07
Friction coefficient μ [-]	LogNormal	0.40	0.40	0.40	0.40	0.40

*factor k correlates the Young's modulus and compressive strength: $E = K \cdot f_c$

Numerical models

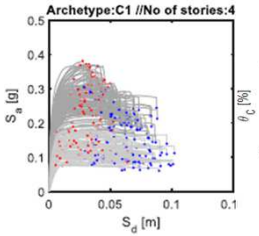


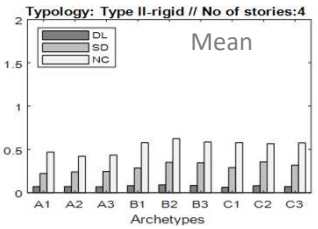


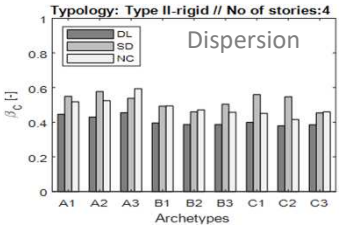
Equivalent frame modelling strategy

Definition of the representative masonry building stock

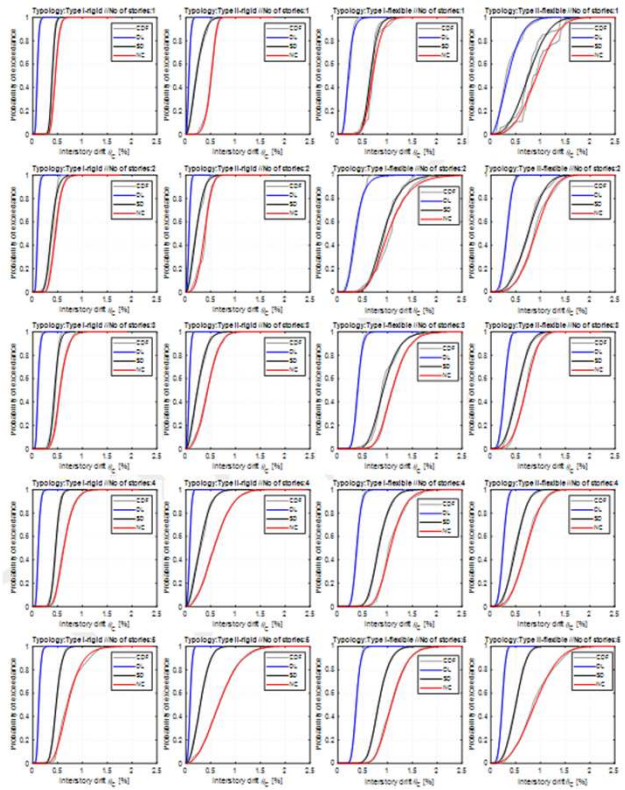
Variability in the building's capacity and fragility curves

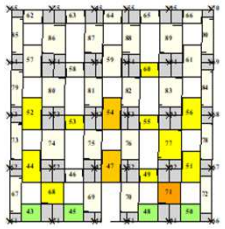


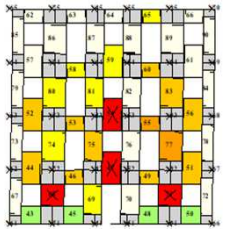


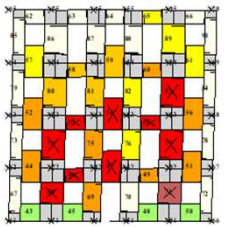


Limit states: Damage limitation (DL), Significant damage (SD) and Near Collapse(NC)

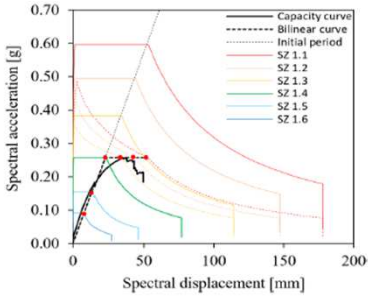


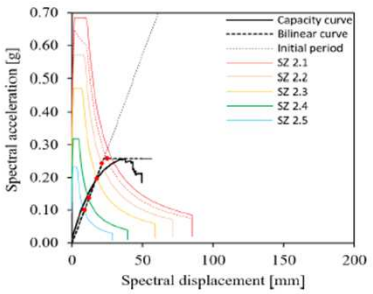

DL


SD

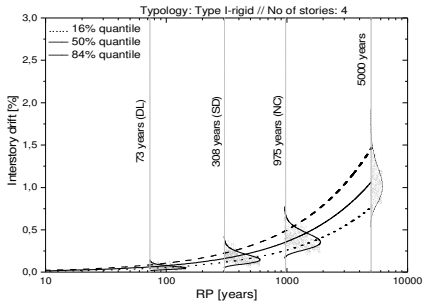

NC

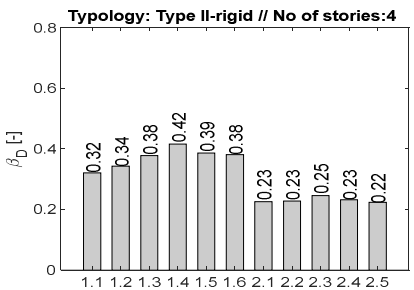
Variability in the seismic response



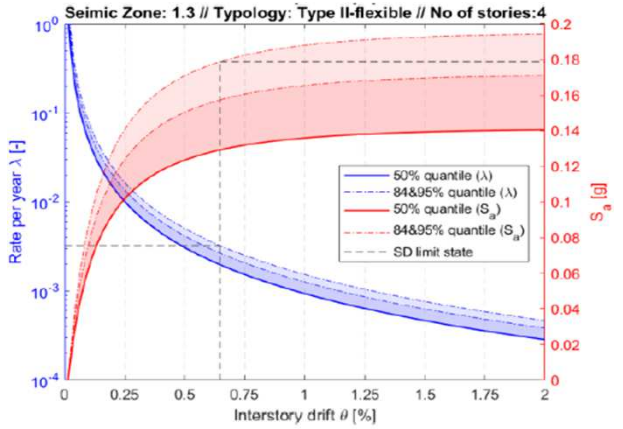


N2 method for the seismic performance.





Vulnerability curves for seismic assessment



Overview of the work done

4. Development of Expeditious Methods for Seismic Assessment of Masonry Buildings

Summary and main topics

- Seismic performance obtained from the previous analysis for all capacity curves (per se), considering all seismic actions soil types A, B and C. Only in-plane mechanisms are simulated. The out-of-plane mechanisms are not considered or are prevented in EC8-3;

- A closed-form solution was derived for the annual exceedance probability assuming an elastic-perfectly-plastic behavior (limit state defined in terms of maximum spectral acceleration);

- Derive a relationship between the reliability index of the structures and the seismic coefficient;

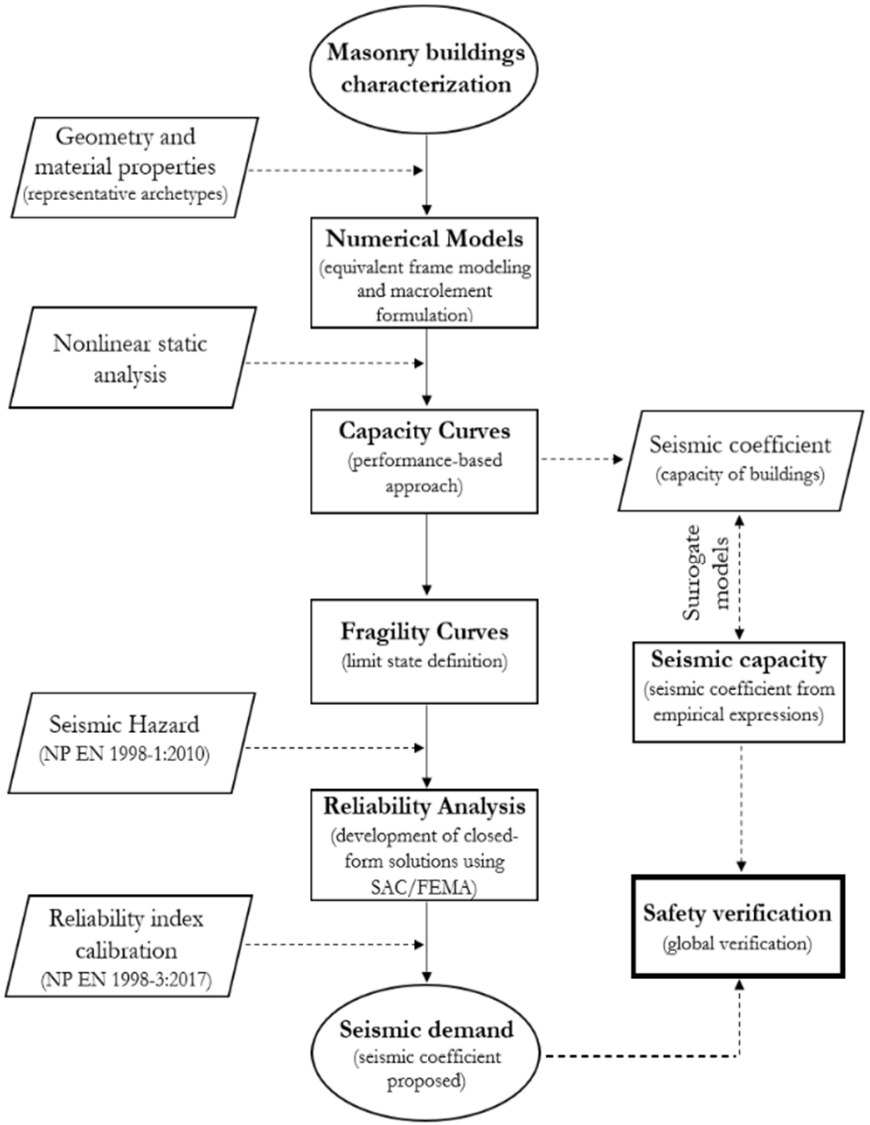
- The reliability index to be required is adjusted in compliance with EC8-3, for the significant damage (SD) limit state and Tr=308 years for a global global safety verification ;

- Expeditious methos are proposed for seismic assessment depending on the evaluated parameter: ratio between the walls area and floor area (method I) or seismic coefficient (method II);

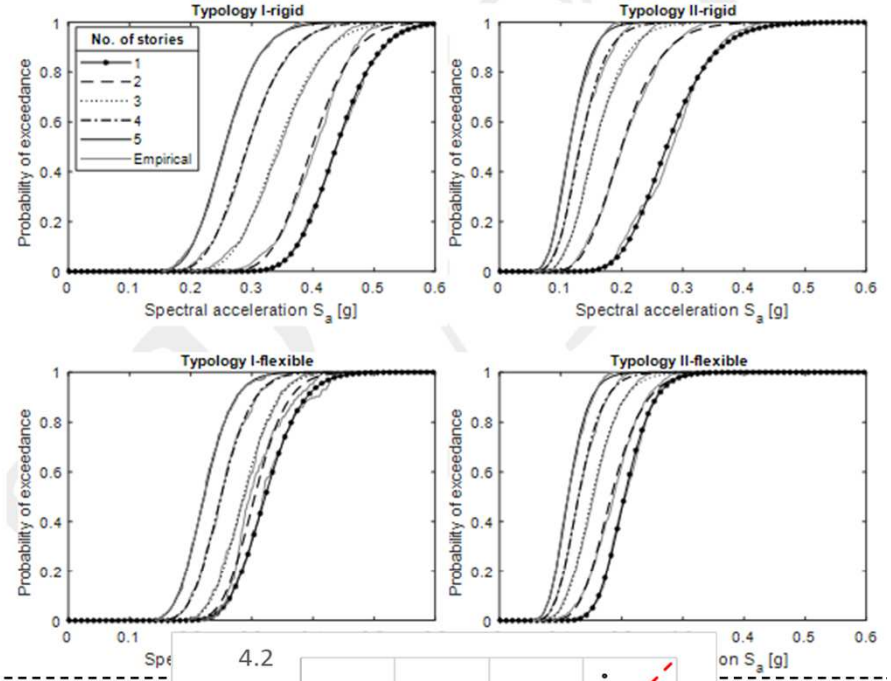
- The compliance of the simplified methods (method I and II) and the reference method or method III (Eurocode) is assessed by confidence tests;

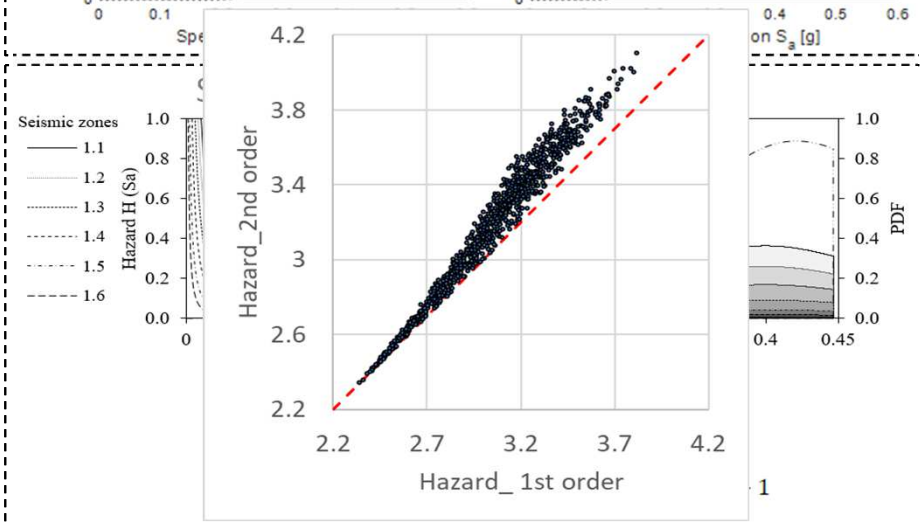
Expeditious methods: formulation and methodology

Flowchart for development of the expeditious methods



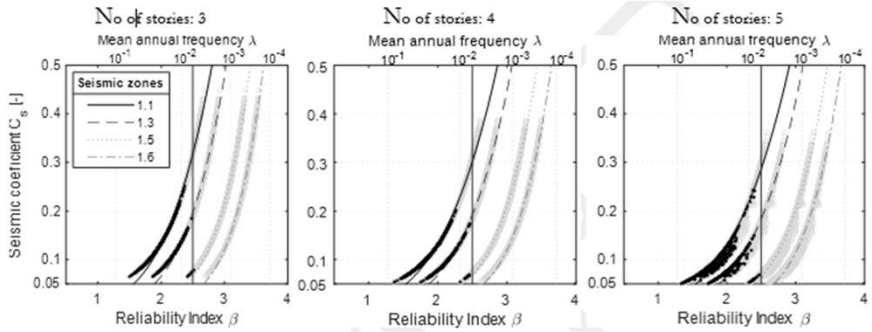
Limit state definition and fragility curves





Expeditious methods and requirements

Expeditious methods: method II



Seismic demand

Number of stories - rigid diaphragms

Seismic Zone	1			2			3			4			5		
	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
1.1	0.36	0.48	0.52	0.33	0.42	0.48	0.31	0.39	0.44	0.29	0.36	0.40	0.28	0.34	0.38
1.2	0.29	0.39	0.46	0.26	0.35	0.40	0.25	0.33	0.37	0.24	0.31	0.35	0.23	0.30	0.33
1.3	0.21	0.29	0.35	0.19	0.27	0.31	0.19	0.25	0.30	0.18	0.24	0.28	0.18	0.23	0.27
1.4	0.12	0.18	0.22	0.12	0.17	0.21	0.12	0.17	0.20	0.12	0.16	0.20	0.11	0.16	0.19
1.5	0.06	0.09	0.12	0.06	0.09	0.11	0.06	0.09	0.11	0.06	0.09	0.11	0.06	0.09	0.11
1.6	0.03	0.05	0.06	0.03	0.05	0.06	0.03	0.05	0.06	0.03	0.05	0.06	0.03	0.05	0.06
2.1	0.33	0.44	0.51	0.29	0.38	0.44	0.23	0.30	0.34	0.17	0.23	0.27	0.14	0.19	0.22
2.2	0.29	0.39	0.45	0.25	0.34	0.39	0.20	0.27	0.31	0.15	0.21	0.24	0.12	0.16	0.19
2.3	0.34	0.45	0.51	0.30	0.38	0.42	0.24	0.30	0.34	0.18	0.24	0.27	0.14	0.19	0.22
2.4	0.20	0.29	0.35	0.18	0.26	0.31	0.15	0.21	0.25	0.11	0.16	0.19	0.08	0.12	0.15
2.5	0.13	0.20	0.25	0.12	0.18	0.22	0.10	0.15	0.18	0.07	0.11	0.13	0.05	0.08	0.10

Number of stories - flexible diaphragms

Seismic Zone	1			2			3			4			5		
	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C	Soil A	Soil B	Soil C
1.1	0.31	0.41	0.47	0.28	0.36	0.40	0.24	0.31	0.35	0.21	0.27	0.30	0.18	0.24	0.26
1.2	0.27	0.37	0.42	0.24	0.32	0.37	0.22	0.28	0.32	0.18	0.24	0.27	0.16	0.21	0.24
1.3	0.20	0.28	0.33	0.18	0.25	0.29	0.16	0.22	0.26	0.13	0.18	0.22	0.11	0.16	0.19
1.4	0.12	0.18	0.21	0.11	0.16	0.20	0.10	0.14	0.17	0.08	0.12	0.14	0.07	0.10	0.12
1.5	0.06	0.10	0.12	0.06	0.09	0.11	0.05	0.08	0.10	0.04	0.06	0.08	0.04	0.06	0.07
1.6	0.03	0.05	0.06	0.03	0.05	0.06	0.03	0.04	0.05	0.02	0.03	0.04	0.02	0.03	0.04
2.1	0.21	0.29	0.33	0.14	0.19	0.23	0.10	0.15	0.18	0.08	0.12	0.15	0.07	0.10	0.13
2.2	0.18	0.25	0.29	0.11	0.16	0.20	0.08	0.12	0.15	0.07	0.10	0.12	0.06	0.09	0.11
2.3	0.21	0.28	0.32	0.13	0.19	0.22	0.10	0.14	0.17	0.08	0.12	0.14	0.07	0.10	0.12
2.4	0.12	0.18	0.21	0.07	0.11	0.14	0.05	0.08	0.10	0.04	0.06	0.08	0.03	0.05	0.07
2.5	0.08	0.13	0.16	0.05	0.08	0.10	0.03	0.05	0.07	0.03	0.04	0.06	0.02	0.04	0.05

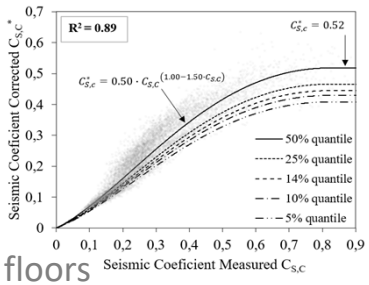
Seismic capacity

$$C_{s,c} = \frac{\sum_{i=1}^{n} V_{H,i}}{W_E} = \frac{\sum_{i=1}^{n} \min\left(V_{flk,i}, V_{cdk,i}, V_{clk,i}\right)}{W_E}$$

$$V_{flk,i} = \frac{\sigma_0 \cdot t \cdot l^2 \left(1 - 1.15 \cdot \frac{\sigma_0}{f_k}\right)}{2 \cdot \alpha \cdot h}$$

$$V_{cdk,i} = l \cdot t \cdot \frac{f_{tk}}{b} \cdot \sqrt{\frac{\sigma_0}{f_{tk}} + 1}$$

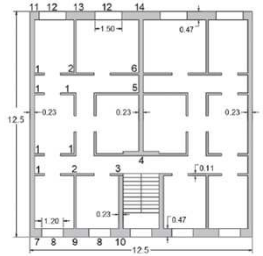
$$V_{clk,i} = l \cdot t \cdot f_{v0k} + \mu \cdot \sigma_0$$



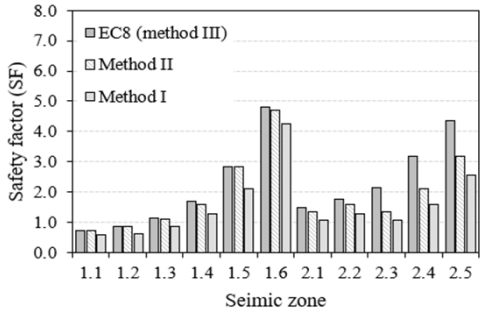
Rigid floors

Confidence tests and case study

Seismic Zone	Rigid diaphragm			Flexible diaphragm		
	Compliance	False Negative	False Positive	Compliance	False Negative	False Positive
1.1	55.5%	43.6%	0.8%	58.5%	41.4%	0.0%
1.2	57.7%	40.9%	1.4%	53.6%	45.8%	0.6%
1.3	66.3%	31.1%	2.6%	62.1%	36.8%	1.2%
1.4	75.1%	23.8%	1.1%	84.6%	14.2%	1.2%
1.5	94.1%	5.3%	0.6%	98.7%	1.2%	0.2%
1.6	99.9%	0.0%	0.1%	100.0%	0.0%	0.0%
2.1	44.3%	55.4%	0.3%	75.2%	22.1%	2.6%
2.2	51.1%	48.5%	0.4%	85.1%	13.2%	1.7%
2.3	45.3%	54.6%	0.1%	76.4%	23.3%	0.3%
2.4	73.8%	26.0%	0.2%	98.5%	1.5%	0.1%
2.5	86.0%	13.9%	0.1%	100.0%	0.0%	0.0%
Total mean	68.1%	31.2%	0.7%	81.1%	18.1%	0.7%



Mechanical properties	Exterior walls	Interior walls
Young's modulus E [MPa]	2.00	1.50
Shear modulus G [MPa]	0.84	0.63
Compressive strength f_{ck} [MPa]	4.00	3.00
Diagonal tensile strength f_{dk} [MPa]	0.30	0.30
Cohesion f_{v0k} [MPa]	0.20	0.20
Friction coefficient μ [-]	0.40	0.40
Density ρ [kg/m³]	18.0	15.0



Rigid floors

Requirements for application of the expeditious methods

Applicability criteria	Method I and II	Method III (EC8-3)
Type of masonry	traditional URM	all
Failure mechanisms	in-plane	in-plane (*)
Type of diaphragm	Rigid/flexible	all
Importance class	I e II	all
Number of stories	up to five floors	N/D
Total plan area	up to 350 m²	N/D
Building layout	isolated or in aggregate	N/D
Structural regularity	yes	optional (**)
Interaction of buildings	limited	w/o limitation
Ground type	soils class A, B and C	all
Foundation system	rigid foundations	N/D

Overview of the work done

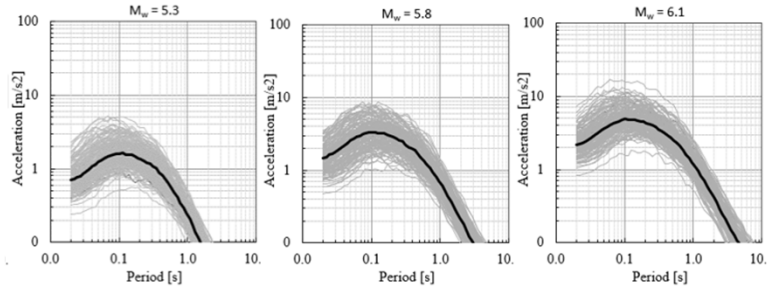
5. Contribution to Seismic Risk Reduction in the Metropolitan Area of Lisbon

Summary and main topics

- Exploring mitigation strategies for seismic risk reduction in MAL based on loss-effectiveness analyses;
- Site-specific ground motion simulated using a non-stationary stochastic model that takes into account the finite fault effects (Alexandra Carvalho, PhD Thesis);
- Seismic risk analysis for the onshore source area of Lower Tagus Valley Fault (LTVF) and different Mw;
- Fragility analyses are derived accounting the previous aleatory and epistemic uncertainty related to the materials and geometry. The dispersion in the seismic demand for the LTVF is also evaluated;
- Exploring a mitigation strategy based on a retrofit solution (Ana Marques, PhD thesis) applied in the interior walls for different levels of strengthening (25%, 50%, 75% and 100%) based on loss-effectiveness analyses;

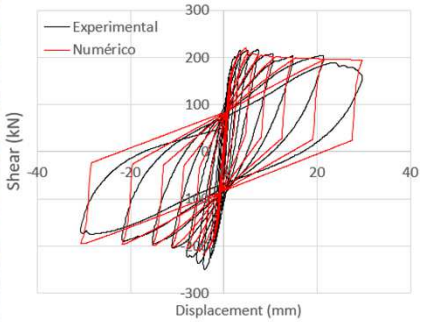
Exploring seismic mitigation strategies (under development)

Seismic action: LTVF Scenario (bedrock)



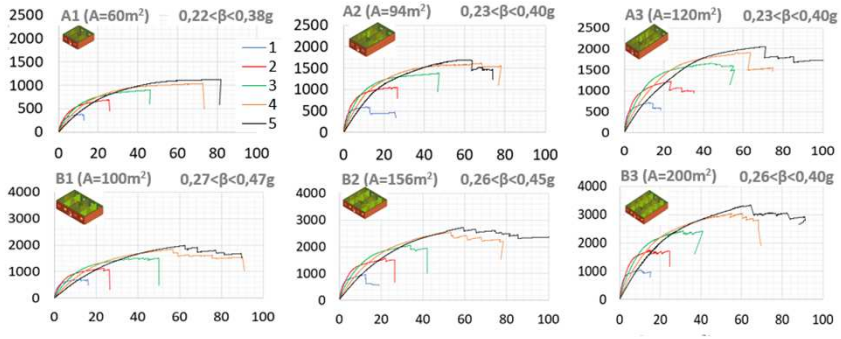
Mw= 4.8, 5.3, 5.8, 6.1, 6.6, 6.8, 7.1 (150 simulations x 7)

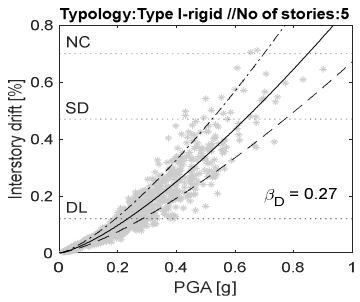
Retrofit solution considered and model calibration

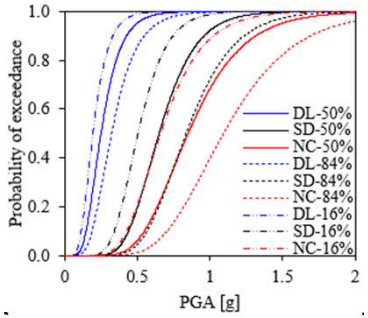


Glass-fibre-reinforced polymers

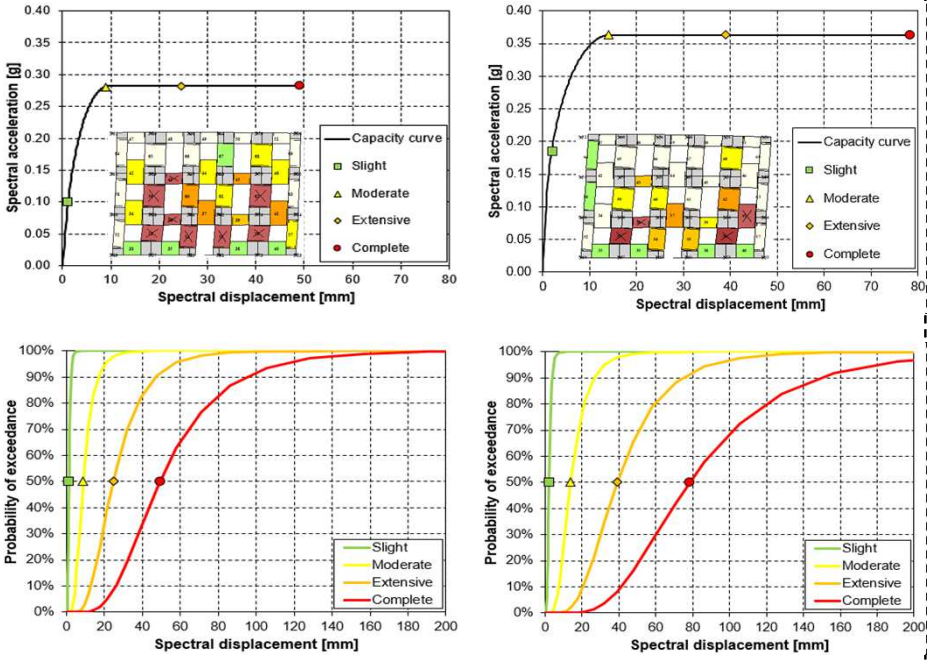
Median curves and seismic fragility (w/o retrofit)







Level of strengthening: 100%



Final comments

- The research performed in the thesis dealt with the seismic safety and vulnerability assessment of masonry buildings in Portugal;
- To cover the huge variability found in these kinds of buildings a large synthetic database was generated constituted of 18.000 buildings (rigid and flexible floors) representative of the Portuguese housing stock;
- Analytical seismic vulnerability assessment and structural reliability analyses were carried out, leading to the development of (expeditious) methods for seismic assessment as an alternative to the reference method defined in the European standard;
- The methods proposed are in line with EC8 and not required explicit numerical analysis;
- The results provided by the expeditious methods are reliable and conservative (> 99% on average);
- The seismic fragility curves proposed in this work account for the variability in the geometry and material properties and can be used for seismic risk studies;
- Loss-effectiveness analyses for a specified solution are under development.

THANK YOU