Recent Shaking Table Tests in Portugal: Lessons Learned

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  - Masonry Structures Without Box Behavior & Rocking Motion
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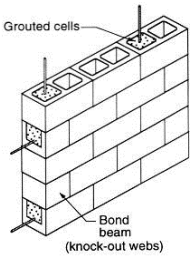
- Just Carried Out & Planned for 2013
  - Masonry Infills #2
  - Tall timber buildings
  - Severe torsional effects
  - Dissipative anchors

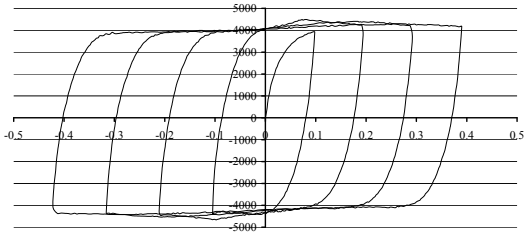
What is Masonry?

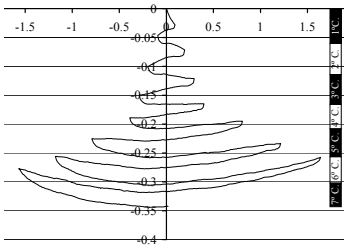


Why is this relevant for mechanics?

Shear testing of stone joints

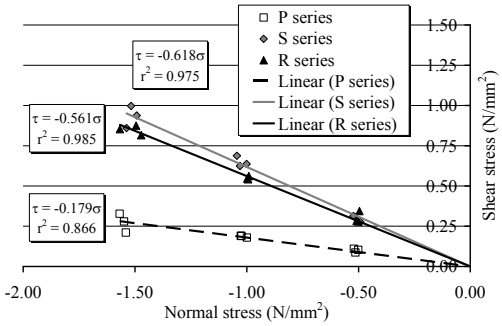
Stress-strain relation





Dilatancy

Failure surface



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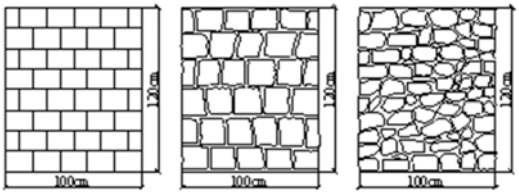
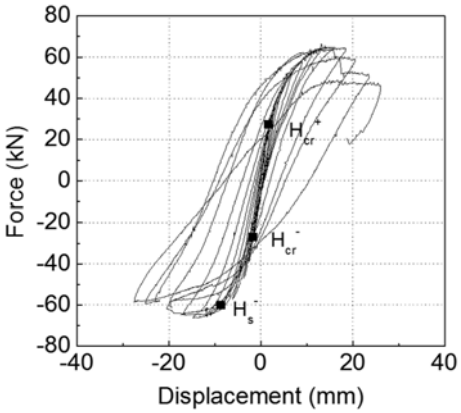


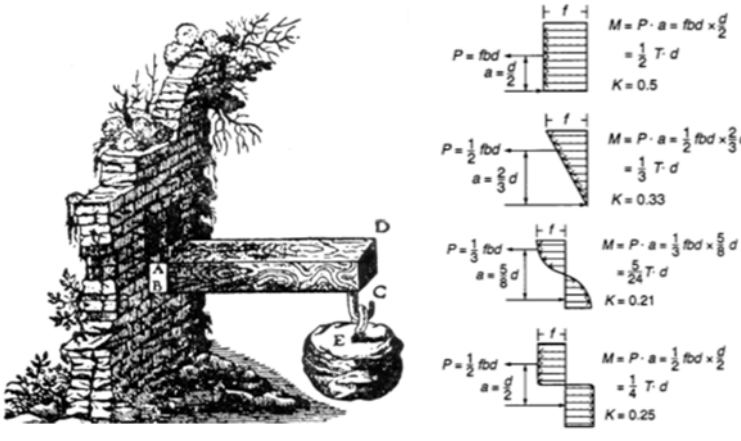


Stone walls

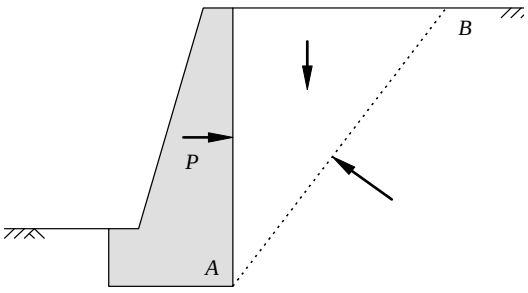
Collapse Mechanism and Strength
Regular – tanϕ = 0.4
Irregular – tanϕ = 0.3
Rubble – tanϕ = 0.2

Linear elastic analysis?

"Ut tensio sic vis" or σ / E = ε is the elasticity law established by R. Hooke in 1676.The theory is so extensively used that its limitations and deficiencies are often forgotten. This is in opposition with early forms of *limit analysis*



Cantilever beam according to Galileo (1638) and evolution of the "hypothesis" for the stress distribution at AB



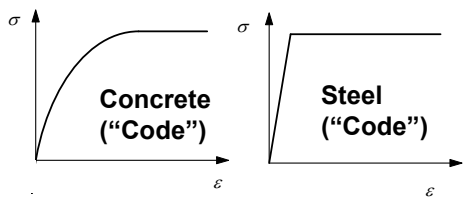
Retaining wall according to Coulomb (1773)

Or non-linear analysis?

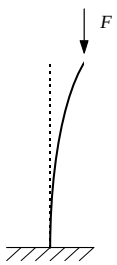
- Structural collapse does not generally coincide with the appearance of the first crack or localized early crushing → elasticity theory is a step back with respect to limit analysis?
- Non-linear analysis includes the full loading process, from absence of loading, through behavior under service loading, until collapse → the most advanced form of structural analysis?
- Interest growing since 1970's → it remains a field for specialists due to complexity (knowledge) and costs (time) involved
- Possibilities are immense and it is often included in commercial software, but an incorrect use can be very dangerous

The use of non-linear analysis

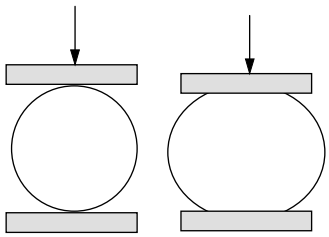
- The modern use of non-linear analysis focuses mostly on:
  - Complex / stringent safety requirement structures (e.g. nuclear plants, dams, bridges…)
  - A tool to understand in detail results from laboratory tests
  - Virtual laboratory for parametric studies → Code drafting / Design rules
  - Existing structures & Earthquake design
- Three types of non-linearities are possible:



Material (or physical) non-linearity

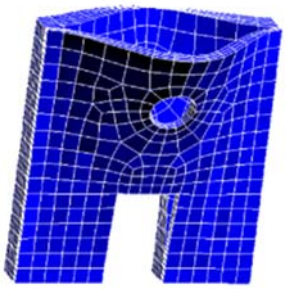


Geometrical non-linearity

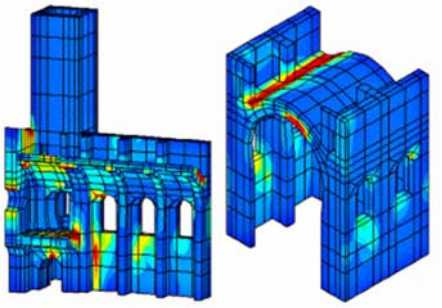


Contact non-linearity

Existing buildings

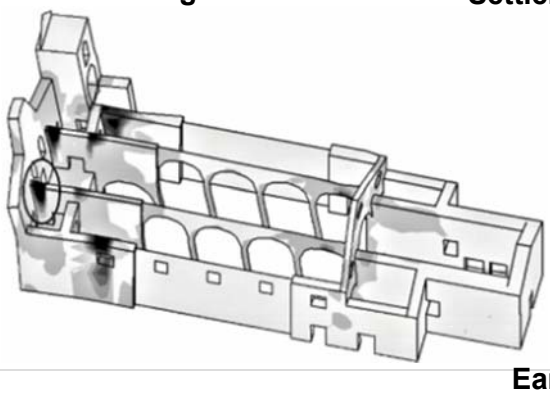


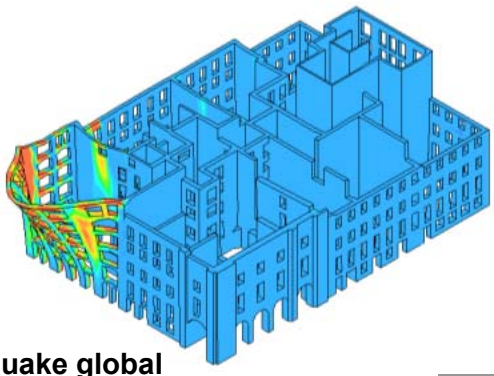
Pounding



Settlements

Vehicles





Earthquake global collapse

Structural Analysis Methods & Earthquake Engineering

- Non-linear time history analysis
- Static non-linear analysis

- Linear elastic time history analysis
- Modal superposition
- Linear static analysis

Simplification

Masonry Structures With Box Behavior

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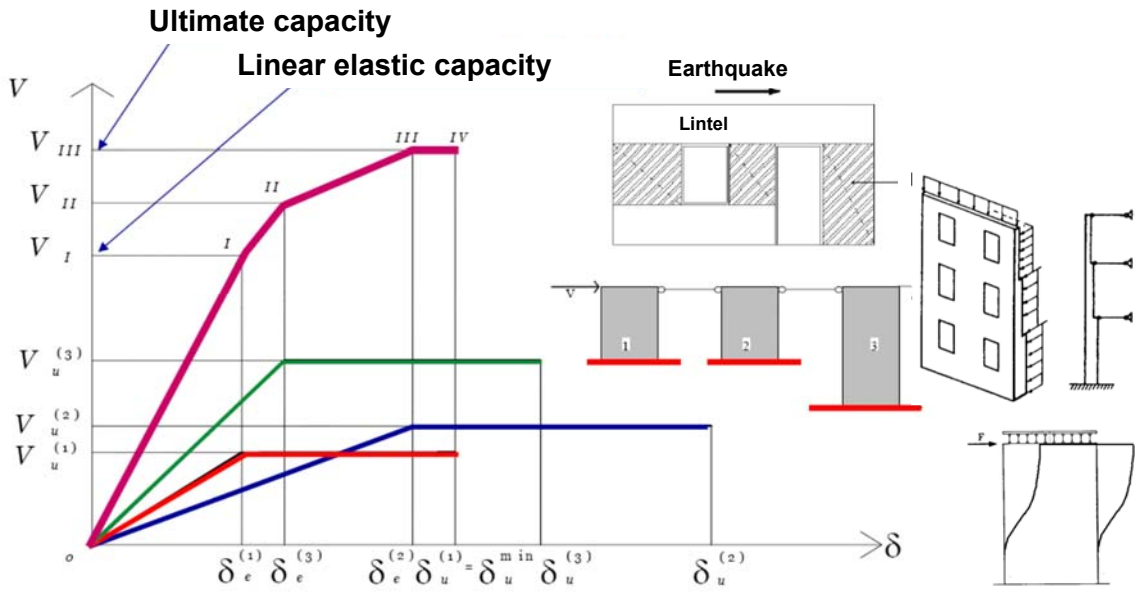
Recent test results: Rigid diaphragm

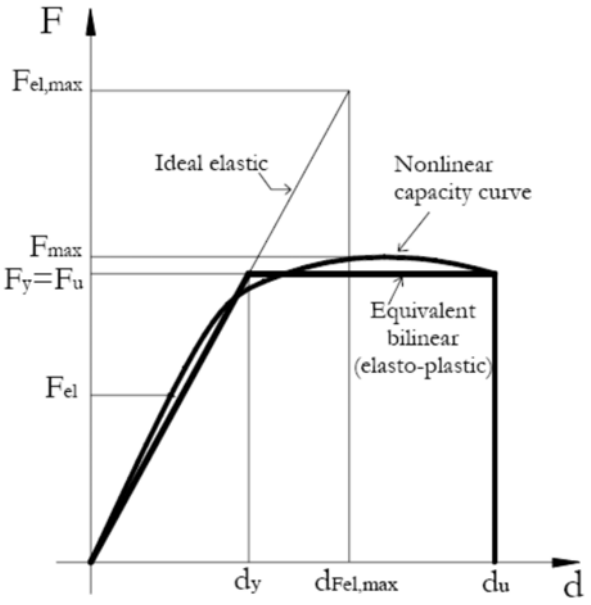
- Worst case scenario: Embedded ring beam + Unfilled vertical joints
- Moderate damage up to 100% of the design earthquake in Lisbon
- Ductile failure for 250% of the design earthquake in Lisbon

"POR" Storey Mechanism



Energy Dissipation Capacity

In a force based method, the non-linear reserve capacity must be considered.
Displacement based techniques are easy to apply and "standard"



For unreinforced masonry buildings with 2 or more storeys:

EC8:

q = 1.5-2.5 (recommended 1.5)

OPCM 3431:

α_u / α_1 (OSR) = 1.8

$q = q_0$ x OSR = 3.6

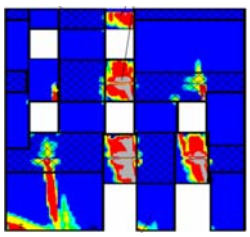
$$q = \frac{F_{el,\max}}{F_{el}} = \frac{F_{el,\max}}{F_y} \cdot \frac{F_y}{F_{el}} = q_0 \cdot \frac{F_y}{F_{el}} = q_0 \cdot OSR$$

Recent Analysis Methods

Research and Development

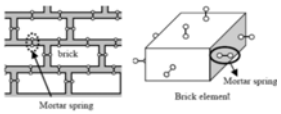
- Continuum Finite Elements (FEM)

  FEM is currently a popular approach in structural analysis software, mostly considering isotropic and homogeneous materials. The computational effort is significant if applied at a full building level



- Discontinuous Models (FEM, DEM, Limit Analysis)

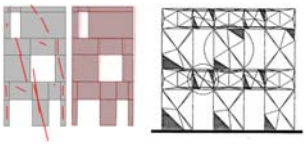
  The use of this models is even more complex in terms of computational efforts, making these methods relevant for the study of structural components and research

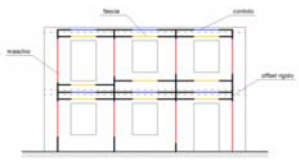


Design

- Structural Component Models: Macro-elements

  These seem to be the most appropriate models for design and assessment, with major contributions in Italy



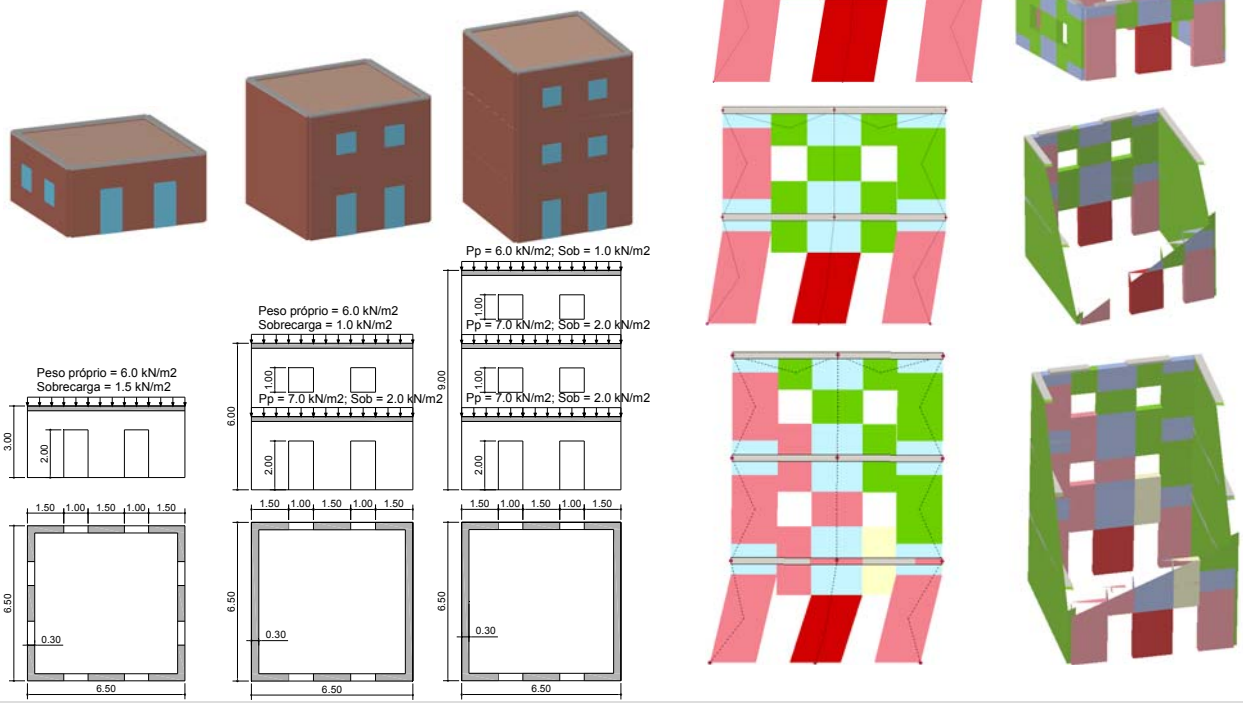


Commercial Software

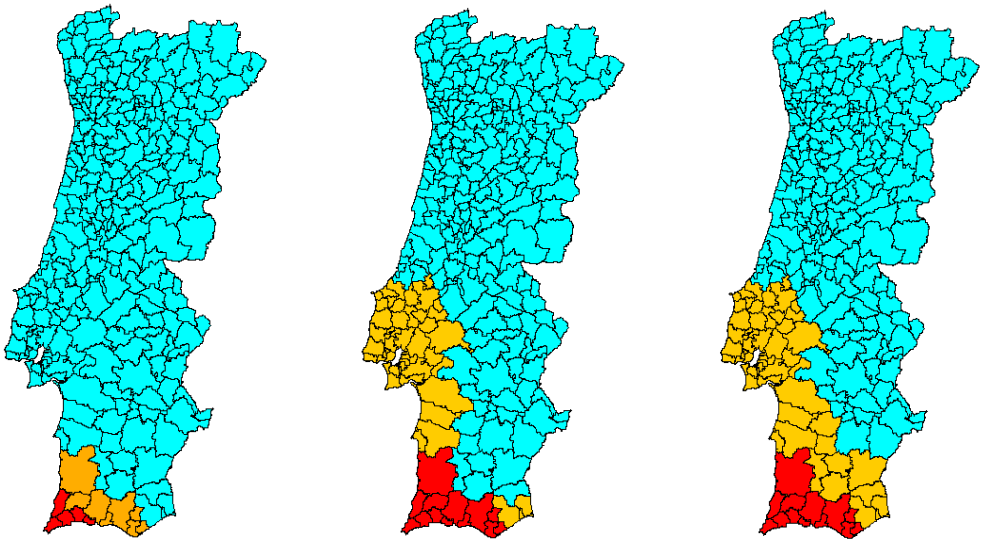
- There are many commercial softwares available in the market for structural masonry, particularly in Italy. Benchmarking was made in two publications: Azores 1998, Eds. C. Sousa Oliveira et al., (2008) and Marques, R., Lourenço, P.B., Possibilities and comparison of structural component models for the seismic assessment of masonry buildings, Computers and Structures, 89 (21-22), p. 2079-2091 (2011).

Program	Country	Code	Approach	Web adress
AEDES	Italy	Italian	FEM and SCM	www.aedes.it
CMT+L	Spain	Eurocode	FEM	www.arktec.com/cmtl.htm
FEDRA	Norway	Eurocode	FEM	www.runet-software.com/FEDRA.htm
WIN-Statik MurDim+	Sweden	?	?	www.strusoft.com
Por 2000	Italy	Italian	SCM	www.newsoft-eng.it/Por2000.htm
TQS CAD/Alvest	Brazil	Brazilian	?	www.tqs.com.br/v13/alvest.htm
Tricalc.13	Spain	Eurocode	FEM	www.arktec.com/new_t13.htm
Tricalc.17	Spain	Spanish	FEM	www.arktec.com/new_t17.htm
WinMason	USA	USA	Storey Mech.	www.archonengineering.com/winmason.html
3Muri	Italy	Italian	SCM	www.stadata.com
ANDILWall	Italy	Italian	SCM	www.crsoft.it/andilwall
MURATS	Italy	Italian	Storey Mech.	www.softwareparadiso.it/murats.htm
Sismur	Italy	Italian	Storey Mech.	www.franiac.it/sismur.html
TRAVILOG	Italy	Italian	Storey Mech.	www.logical.it/software_travilog.aspx
Tecnobit	Italy	Italian	Storey Mech.	www.tecnobit.info/products/murature.php
CDMaWin	Italy	Italian	FEM and SCM	www.stsweb.net/STSWeb/ITA/homepage.htm

Application



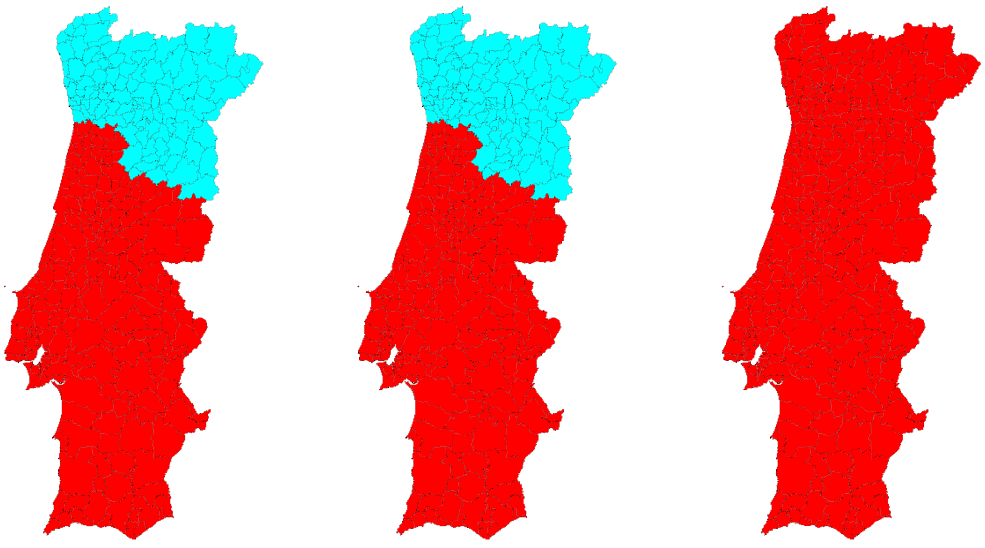
Application: Push-over method / OPCM 3431



1 storey | 2 storeys | 3 storeys

KO | OK for soil type A | OK for soil types A and B

Application: Elastic design (EC8)



1 storey 2 storeys 3 storeys

KO OK for soil type A

Lessons #1

- Modern URM can be built in earthquake countries
- Wrong analysis methods or Wrong codes = Wrong answers
- Adequate models and commercial software, based on pushover analysis, are available for masonry structures with box behavior

Masonry Structures Without Box Behavior

isise

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Existing Masonry Structures

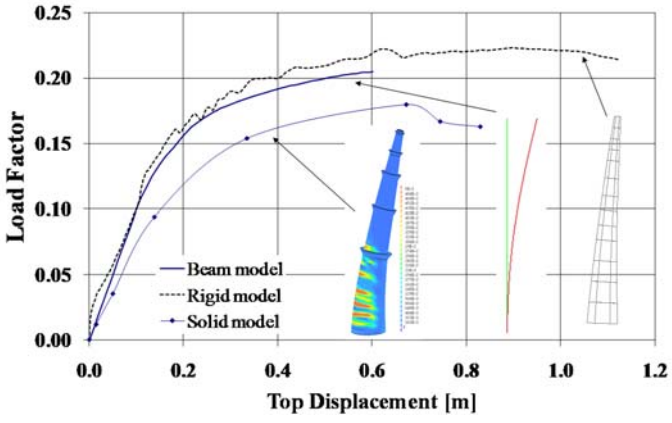
- "Existing built heritage often with high vulnerability: (a) very weak materials; (b) heavy construction; (c) insufficient connections
- Simple measures can help

A. Costa
FEUP+LNEC

Recent Tests: Flexible Diaphragm

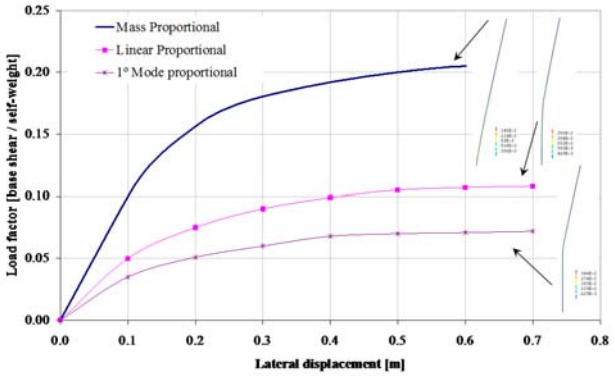
- "Gaioleiro"-type structure (late 19th century / early 20th century)
- Moderate damage for 100% of the design earthquake in Lisbon
- Light strengthening and collapse for 150% of the design earthquake in Lisbon

Push-Over Analysis



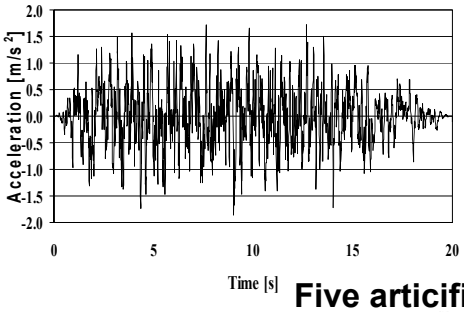
Uniform Mass Distribution

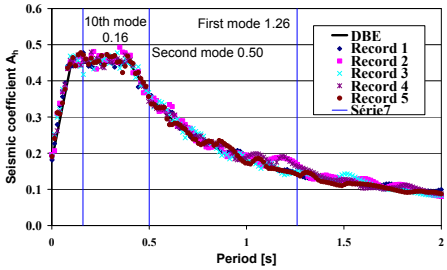
Collapse at the base



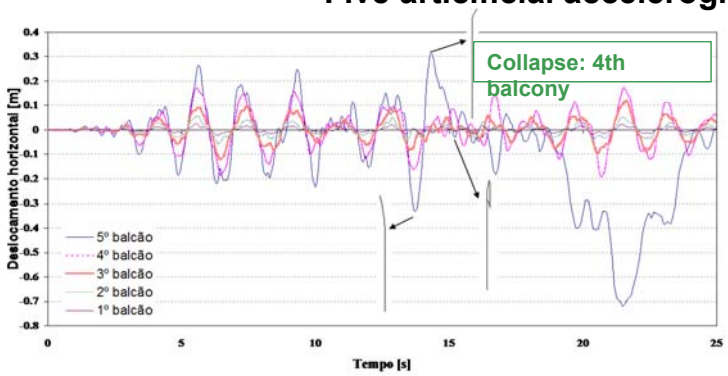
Other Mass Distributions

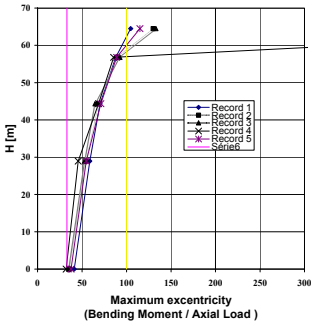
Time History Analysis





Five articificial accelerograms

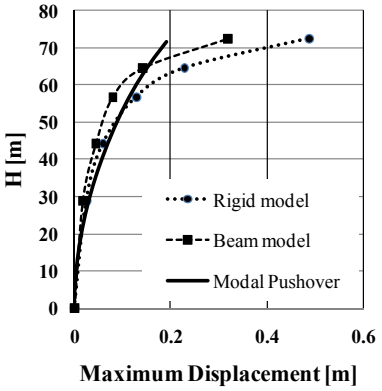


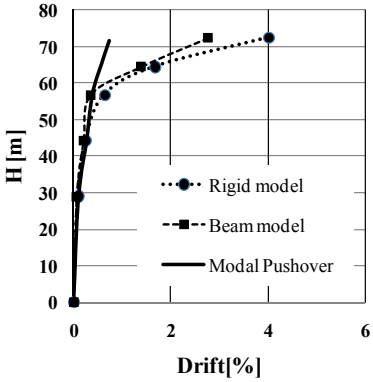


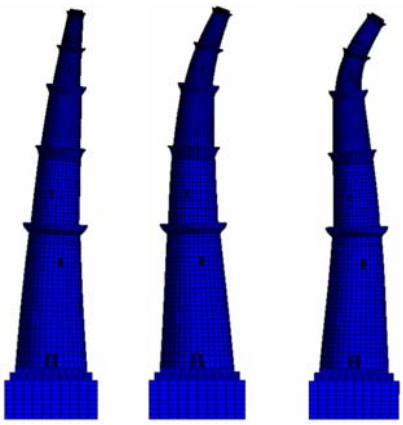
REM

FEM – Collapse for 0.20*g*

Modal Pushover







90% of the total mass, 7 modes

Is adaptative pushover a solution?

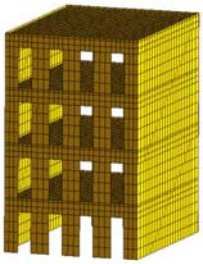
"Gaioleiro" Building

Location: Lisbon

Material: Masonry walls and timber pavements

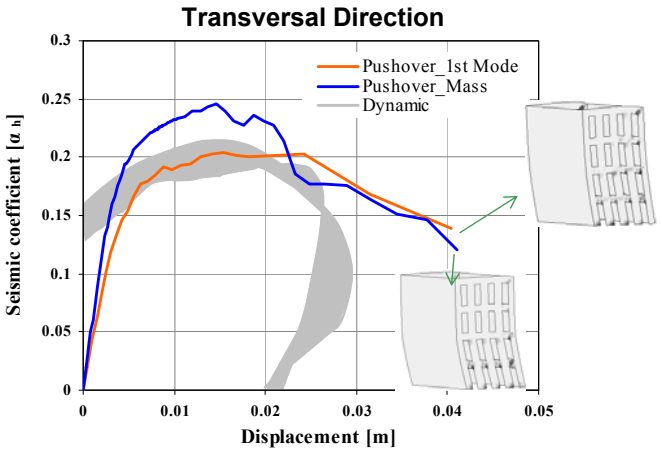
No. of storeys: 4 to 6

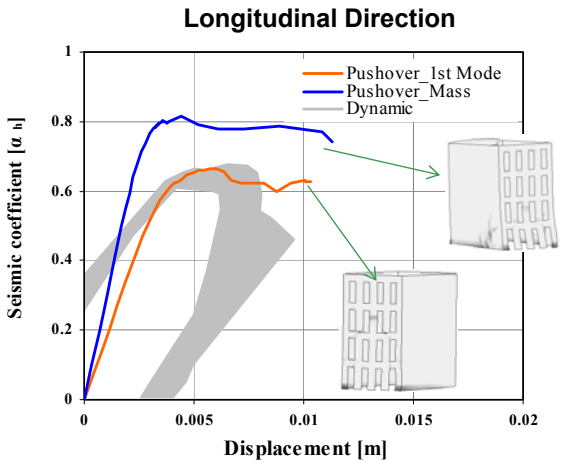
Numerical model



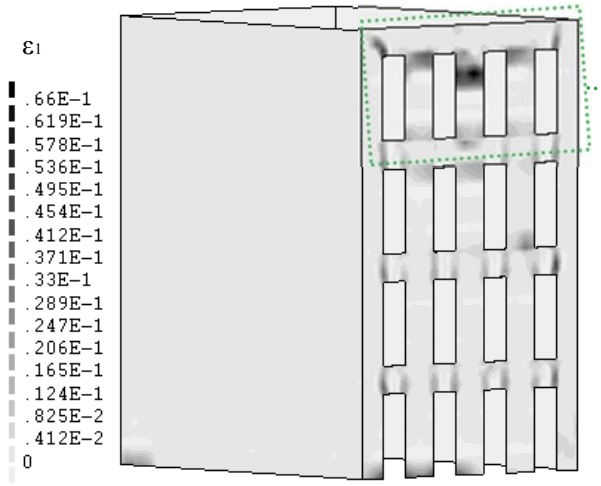
"Gaioleiro" Building

Pushover Analysis

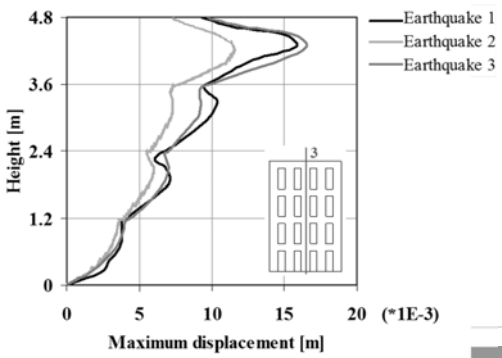




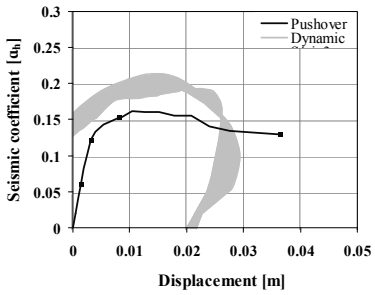
Time History Analysis

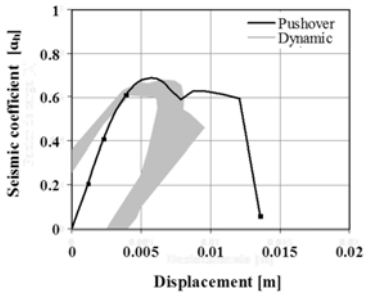


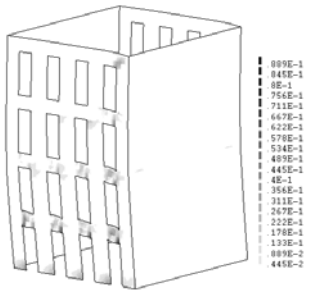
Experimental model



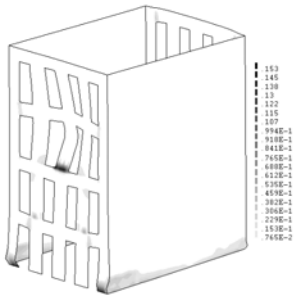
Adaptative Pushover Analysis







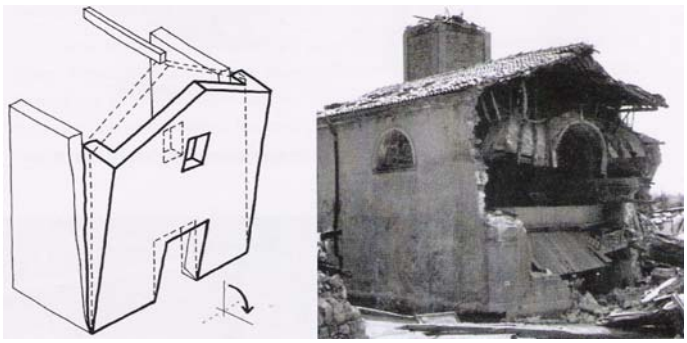
Transversal Direction



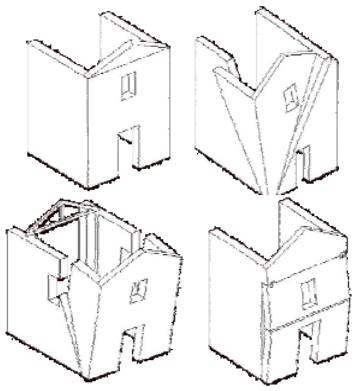
Longitudinal Direction

Design and Assessment = Macro-block analysis?

Limit equilibrium analysis using the principle of virtual work is currently understood as the "best" analysis technique



Overturning

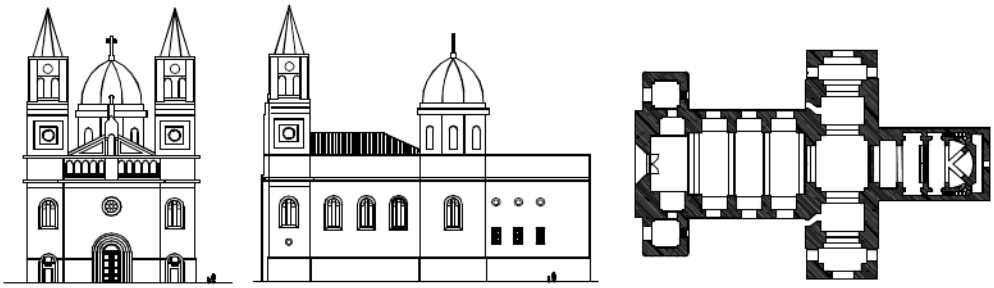


Example

Location: Guimarães

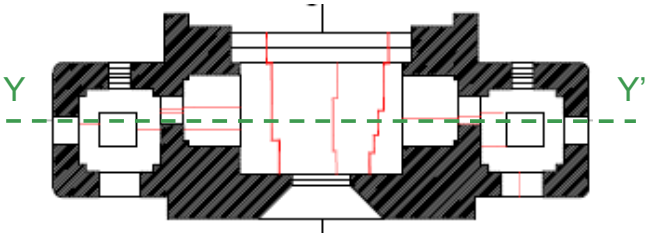
Style: Hybrid, with classical, gothic, renaissance and romanic elements

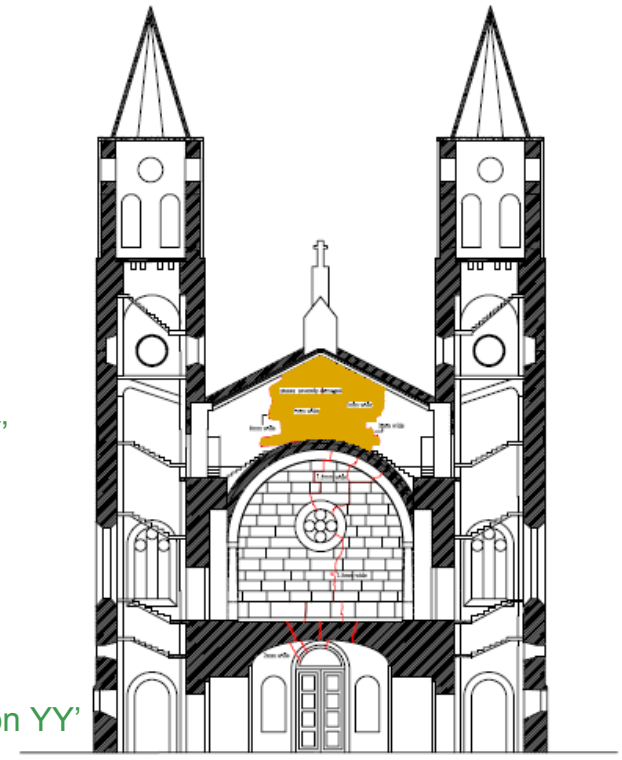
Material: Granite stone masonry



Example

- Cracking Pattern

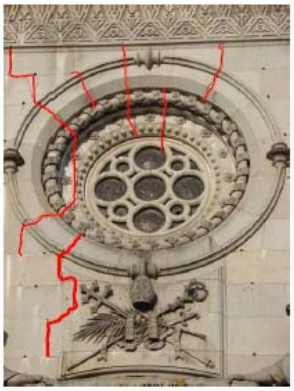


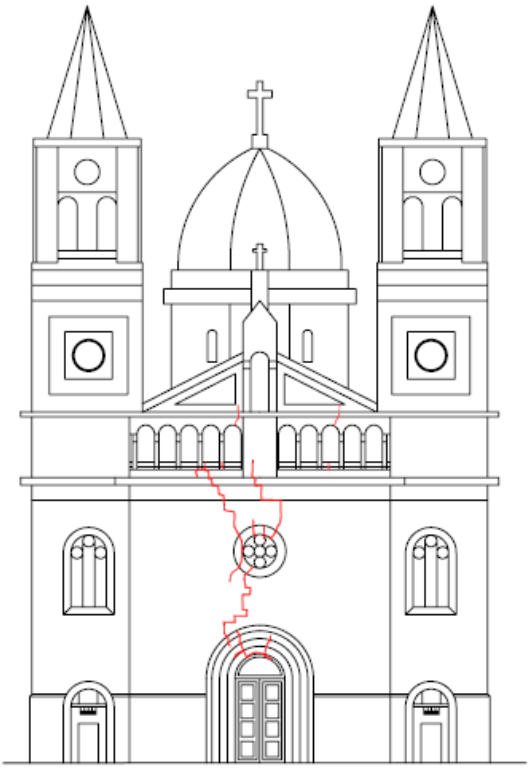


Section YY'

Example

- Cracking pattern

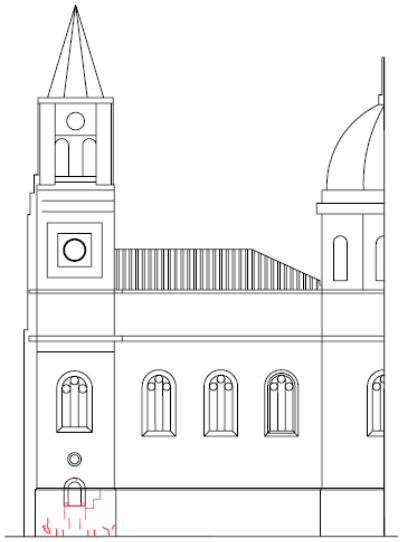




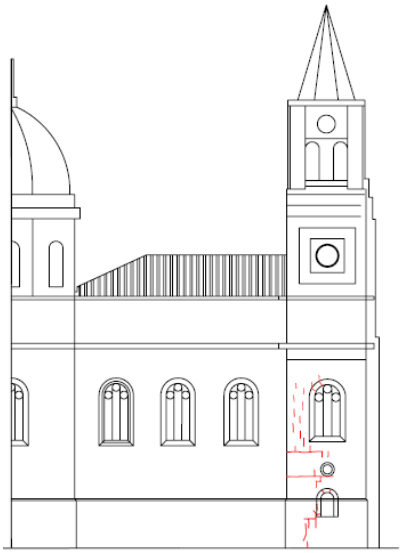
Main façade

Example

- Cracking pattern

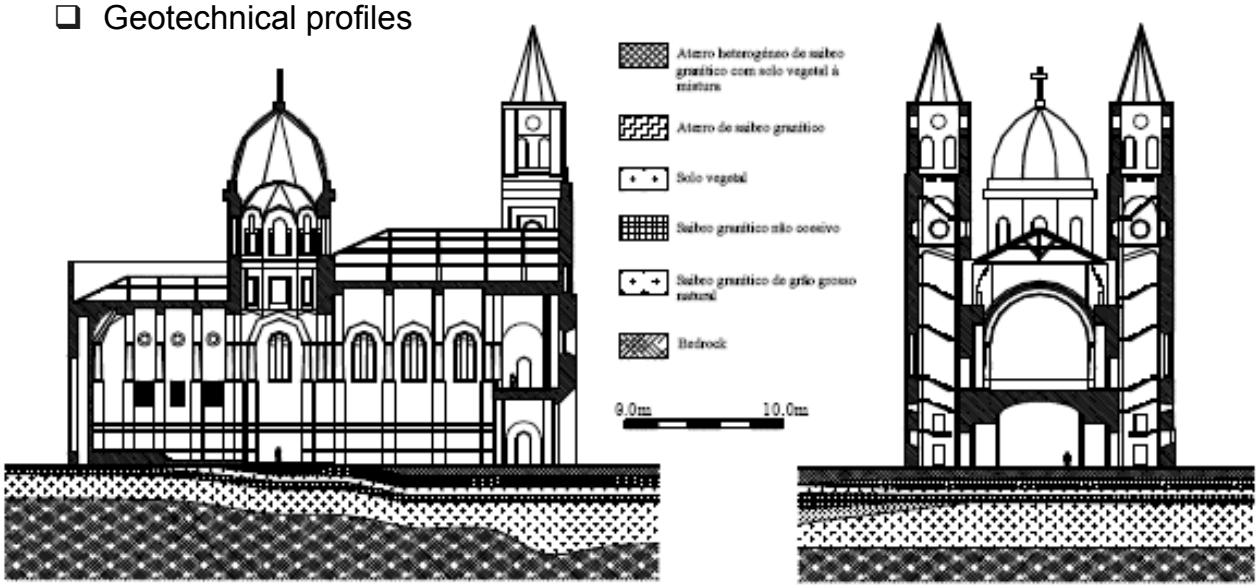


Views



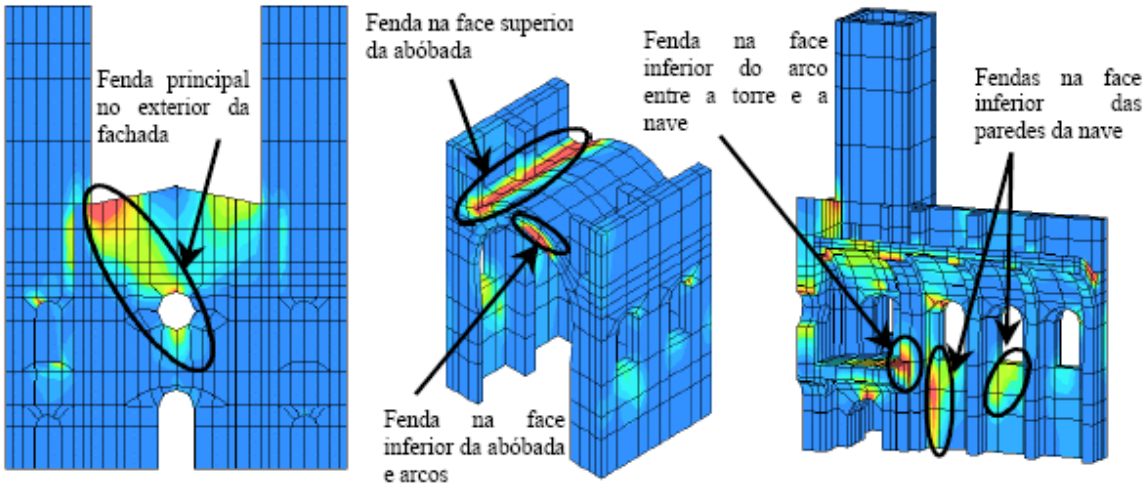
Example

- Geotechnical profiles



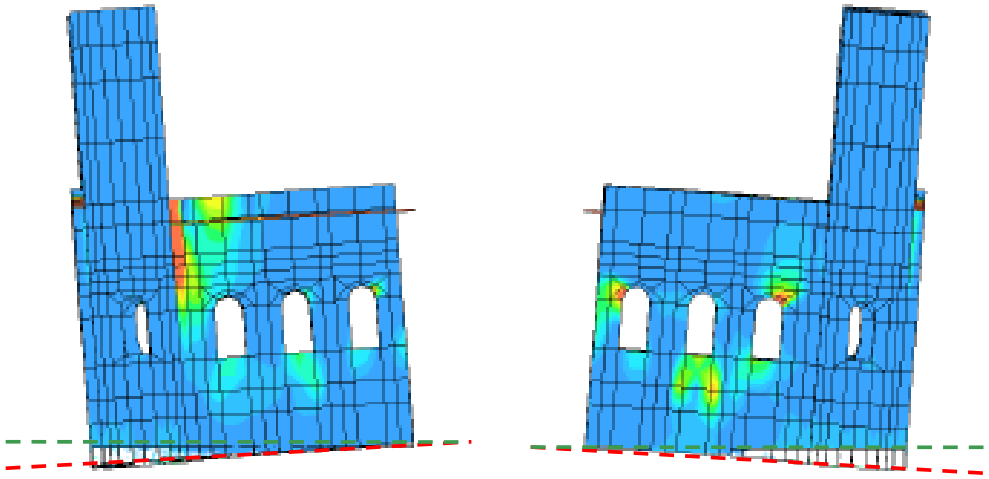
Example

- FEM Model



Example

- Soil structure-**interaction**

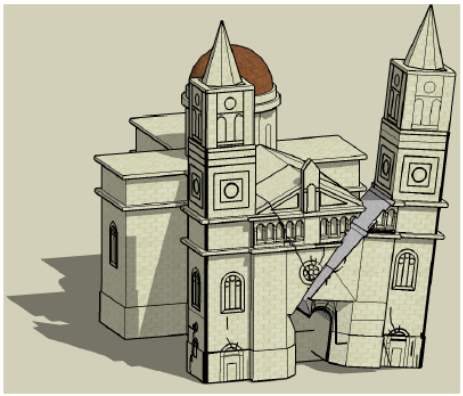


Seismic Analysis

- Four possible mechanisms

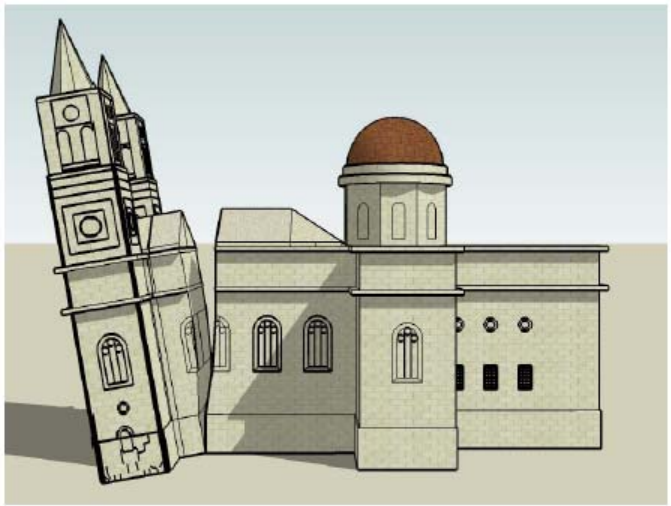
	α_0	0.186
	M*	4343.7 KN
	e*	0.947 m/s^2
Capacity	a_0*	0.197 g
Demand	a_0*	0.063 g
Safety Factor		3.13

Seismic Analysis



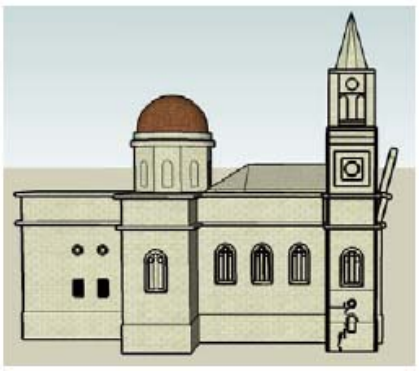
	α_0	0.184
	M*	4254.5 KN
	e*	0.953 m/s^2
Capacity	a_0*	0.193 g
Demand	a_0*	0.086 g
Safety Factor		2.24

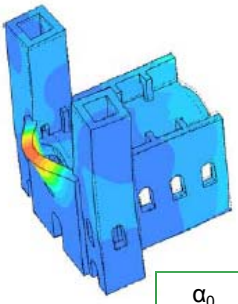
Seismic Analysis



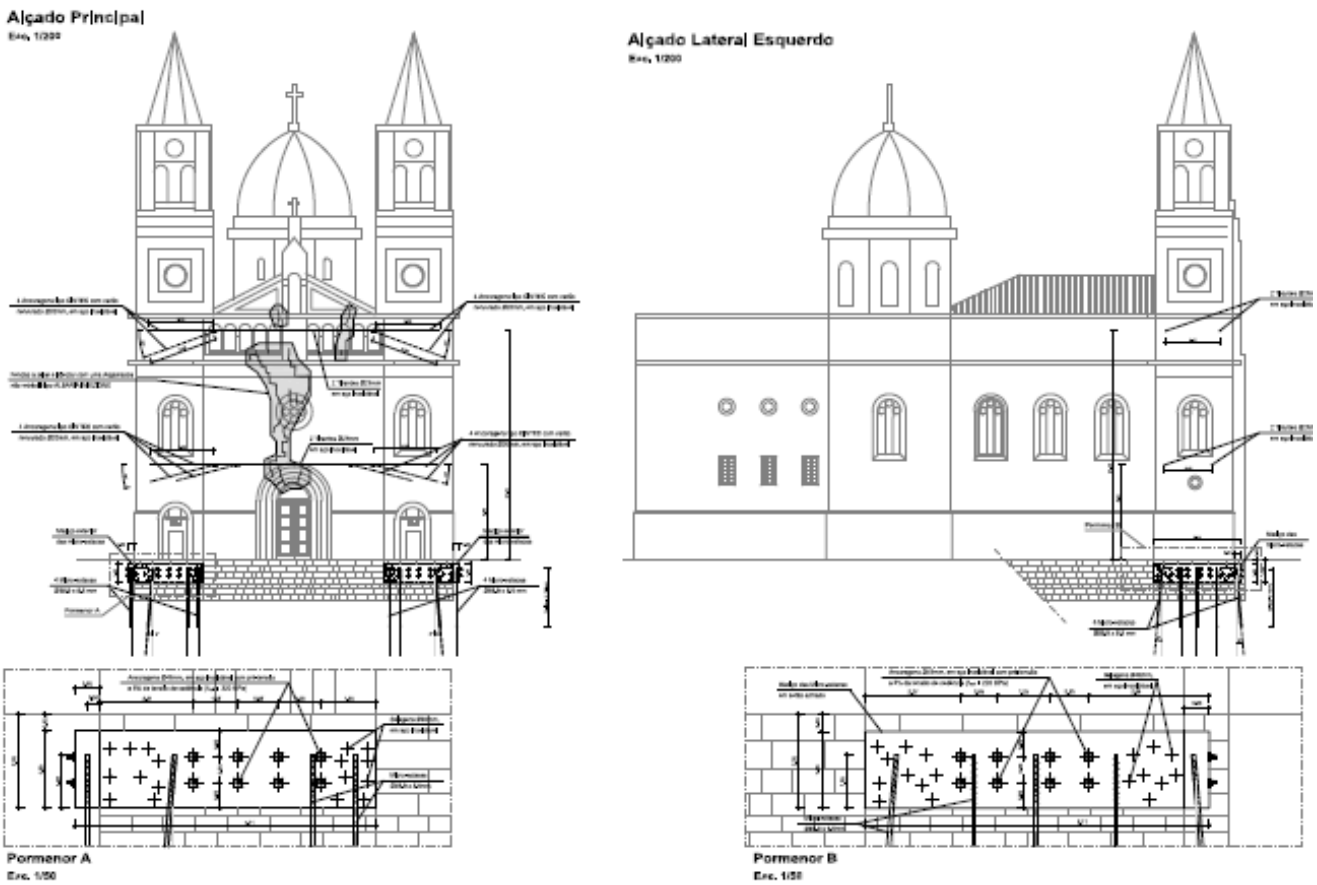
	α_0	0.164
	M*	8830.1 KN
	e*	0.968 m/s^2
Capacity	a_0*	0.169 g
Demand	a_0*	0.087 g
Safety Factor		1.94

Seismic Analysis

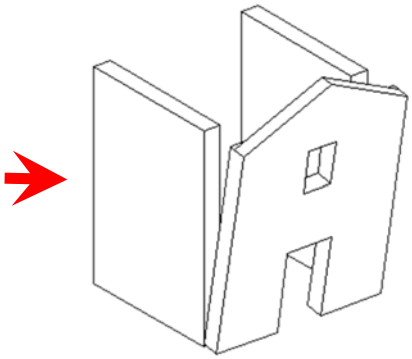


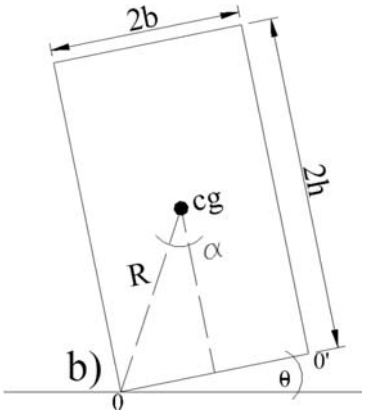


	α_0	0.205
	M*	339.1 KN
	e*	0.982 m/s^2
Capacity	a_0*	0.208 g
Demand	a_0*	0.123 g
Safety Factor		1.69



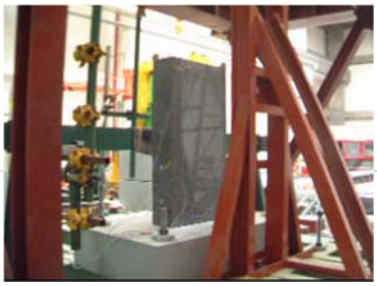
Rocking Motion and Multibody Dynamics



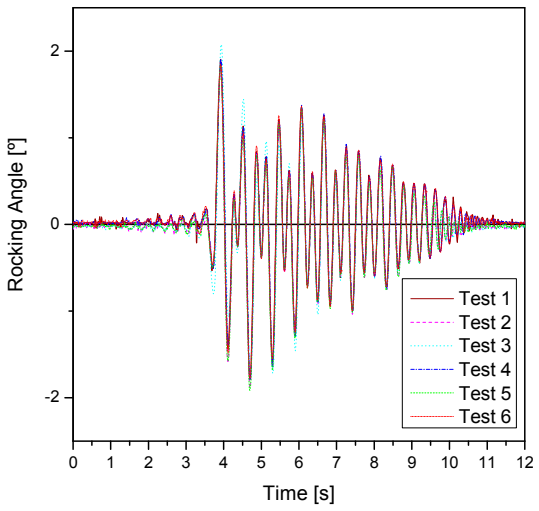


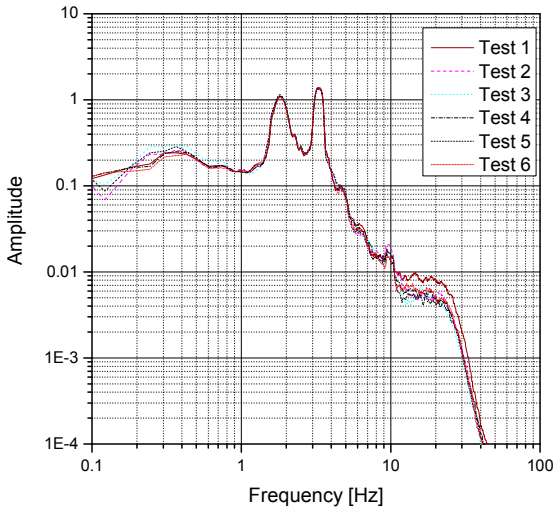
Masonry structures

Inverted pendulum (SDF problem)



Repeatability Test

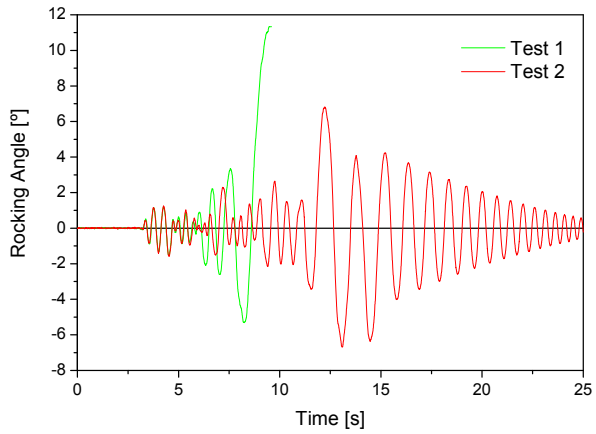




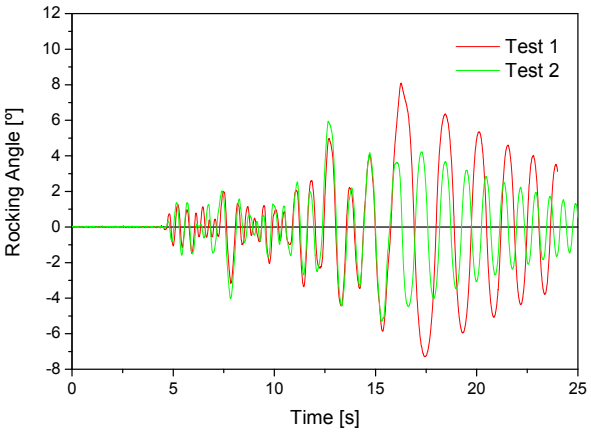
Hanning sine 3.3 Hz, 7 mm (P1)

Fourier Spectra

Random Motion

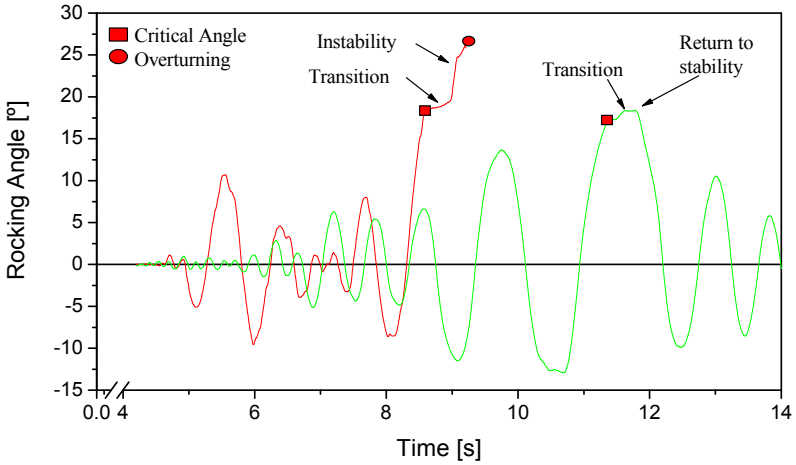


Seismic record 20 – 1.1 (P2)



Seismic record 20 – 1.3 (P2)

Overturning Process



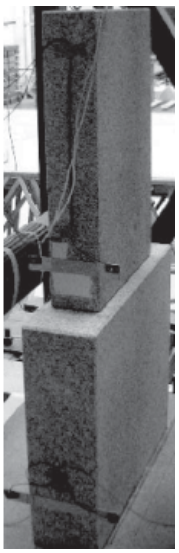
Full results, with:

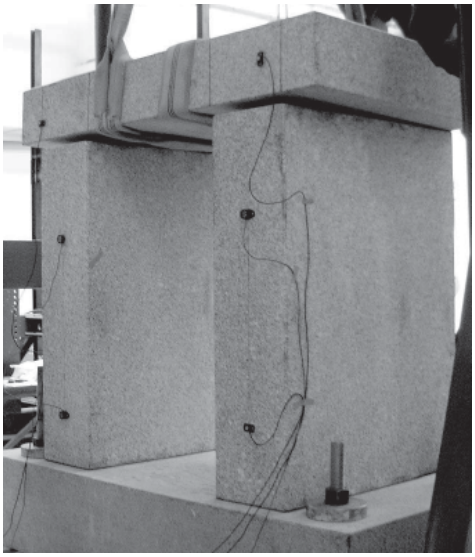
- **Experimental details**
- **Numerical simulation**
- **Stochastic analysis**

On the dynamics of rigid-block structures: Applications to SDOF masonry collapse mechanisms, PhD Thesis, Francisco Prieto

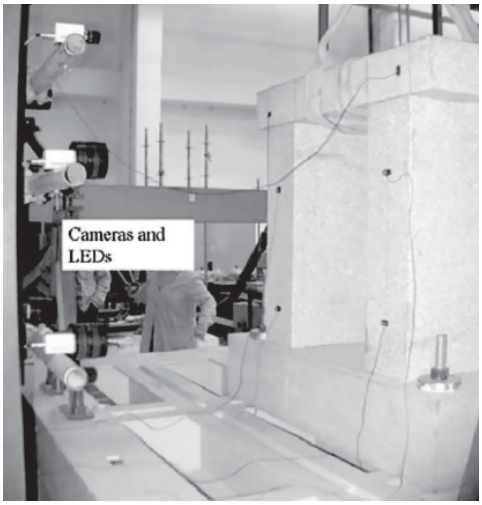
Specimen	Critical Angle [º]		
	Theoretical	Experimental	Difference (%)
2	9.6	11.2	16
4	18.0	20.8	15

Multibody Dynamics



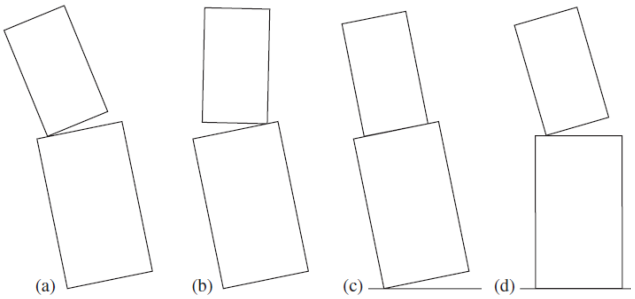


Stacked blocks and trilith

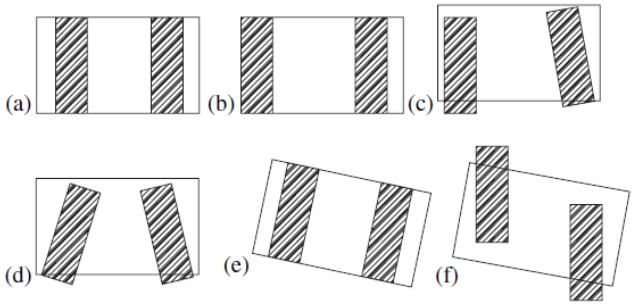


Setup

Multibody Dynamics



Rocking patterns for stacked blocks



Final configurations for trilith

Lessons #2

- Duration of the earthquake is a critical issue for brittle responses (be careful with scaling laws + do we know the duration of earthquakes?)
- Repeatability does not hold for random analysis of brittle structures (probabilistic analysis is required)
- Pushover methods fail to replicate observed failure modes of ancient masonry structures. Adaptive pushover and modal pushover analysis are not better. Macro-block can be a possible solution. But if you use them and fail to use the correct failure modes, the error can be large
- If you use pushover analysis adopt a mass proportional load distribution (uniform horizontal acceleration)

Masonry Infills

Universidade do Minho

Facts

- A (very) old research issue
  - Infill walls continue to fall. Life saving issue

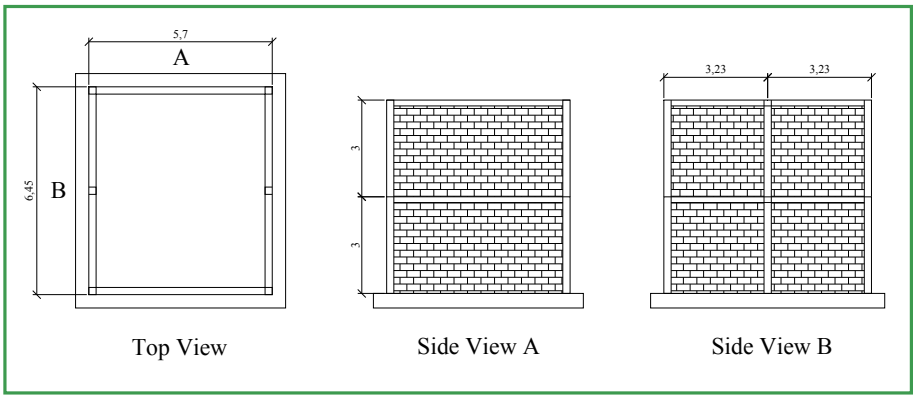
  - Estimated invested in masonry infills in Europe around 45 to 60 billion euro. Greece (Parnitha, Magnitude 5.9, 1999), 60% of the repair costs due to damage in masonry infills, associated finishings and installations (water, electricity, etc.). Insurance companies refers even higher costs (up to 80% of the total value of the building) for repairing and reconstructing non-structural elements. Cost issue

Motivation

- Reality
  - L'Aquila earthquake (2009), Italy

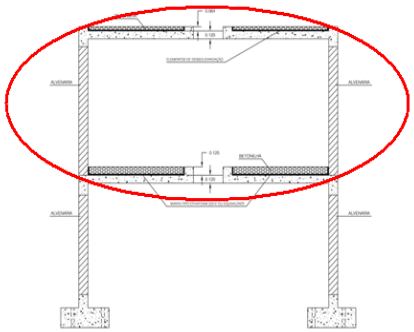
Scope of the project: Shaking table experimental program

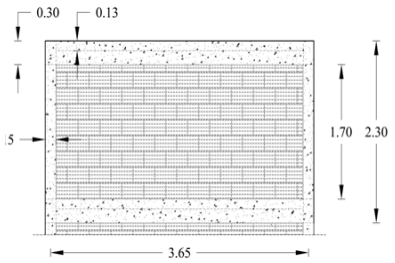
- Broader project and all the tests are based on the same geometry
- Idealization of the geometry was done regarding the buildings constructed in the last 20 years, in Portugal



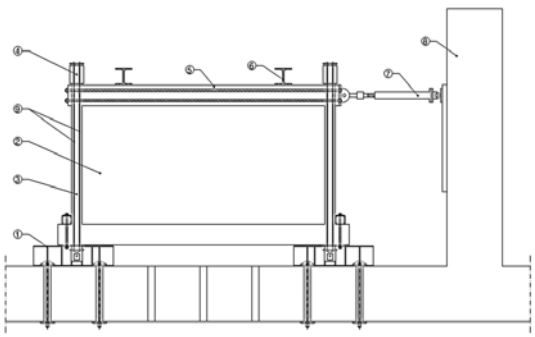
Full scale geometry of study specimens (meters)

Preliminary Static Tests

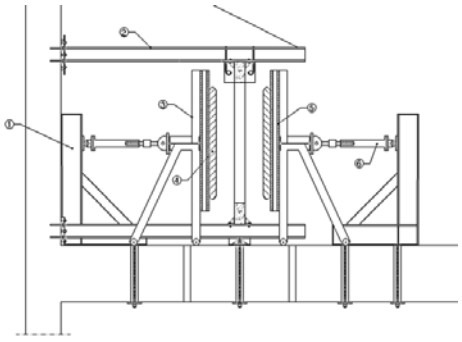




Panel to be tested

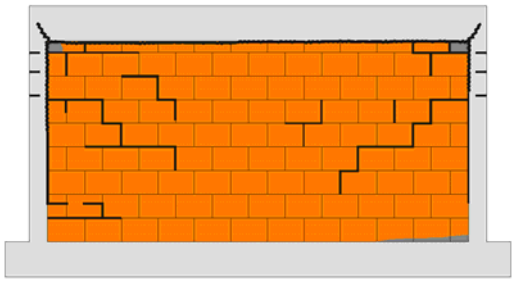


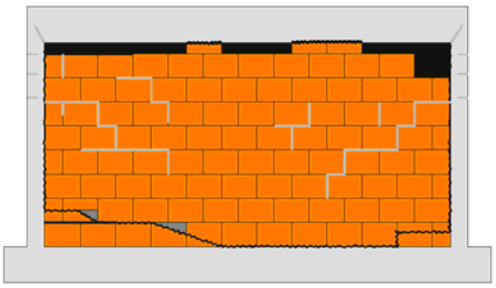
In-plane (cyclic) tests



Out-of-plane cyclic tests

Static tests (I)



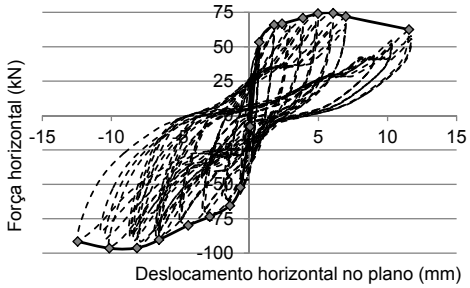


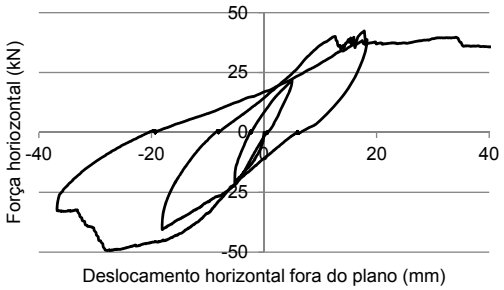
After in-plane test

After out-of-plane test

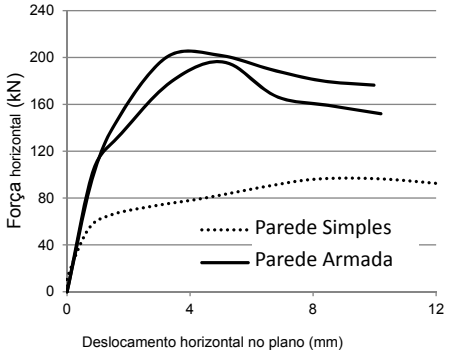
Out-of-plane movement (unreinforced vs. reinforced)

Static tests (II)

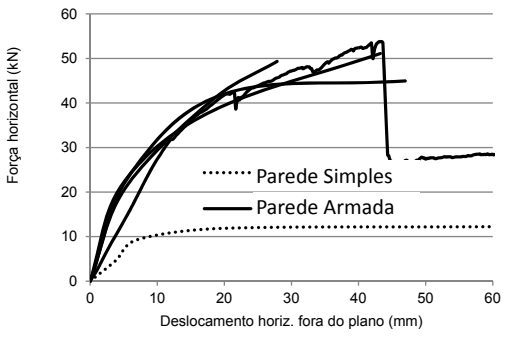




In-plane tests



Out-of-plane tests

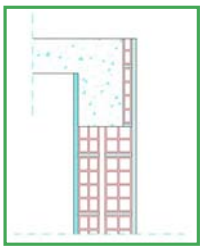


Scope of the project: Shaking table experimental program

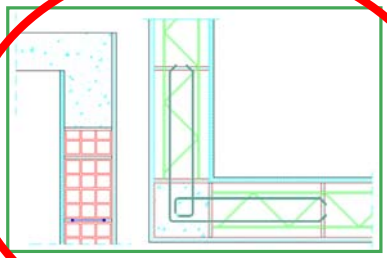
❑Prototype reduced using Cauchy-Froude's Simililitude Law to a scale 1:1,5

❑ Three buildings were designed, each one with a different infill solution and following either the Portuguese standards or Eurocodes (1,2 and 8)

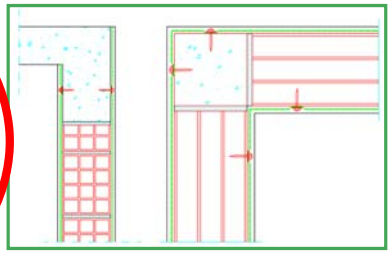
❑One building represents what is built (unreinforced double leaf clay brick masonry infill and older standards) and the other two future possibilities (reinforced single leaf clay brick infill and Eurocodes)



Infill Solution 1

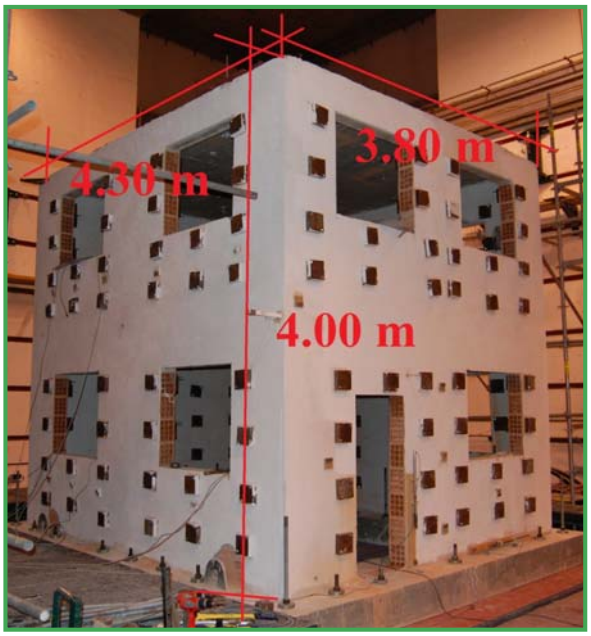


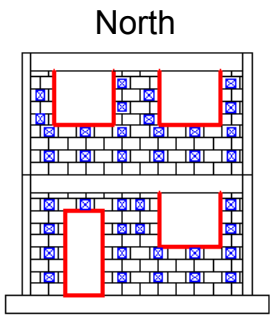
Infill Solution 2

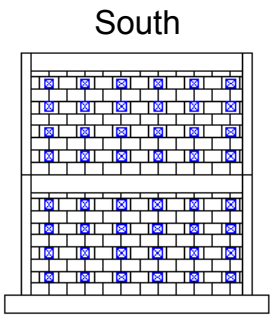


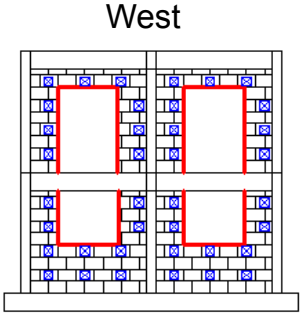
Infill Solution 3

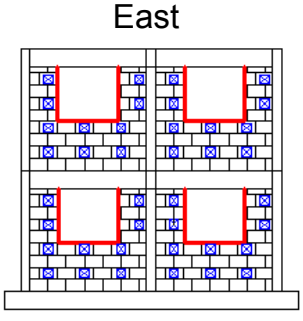
Shaking table test: Shape and dimensions of the model





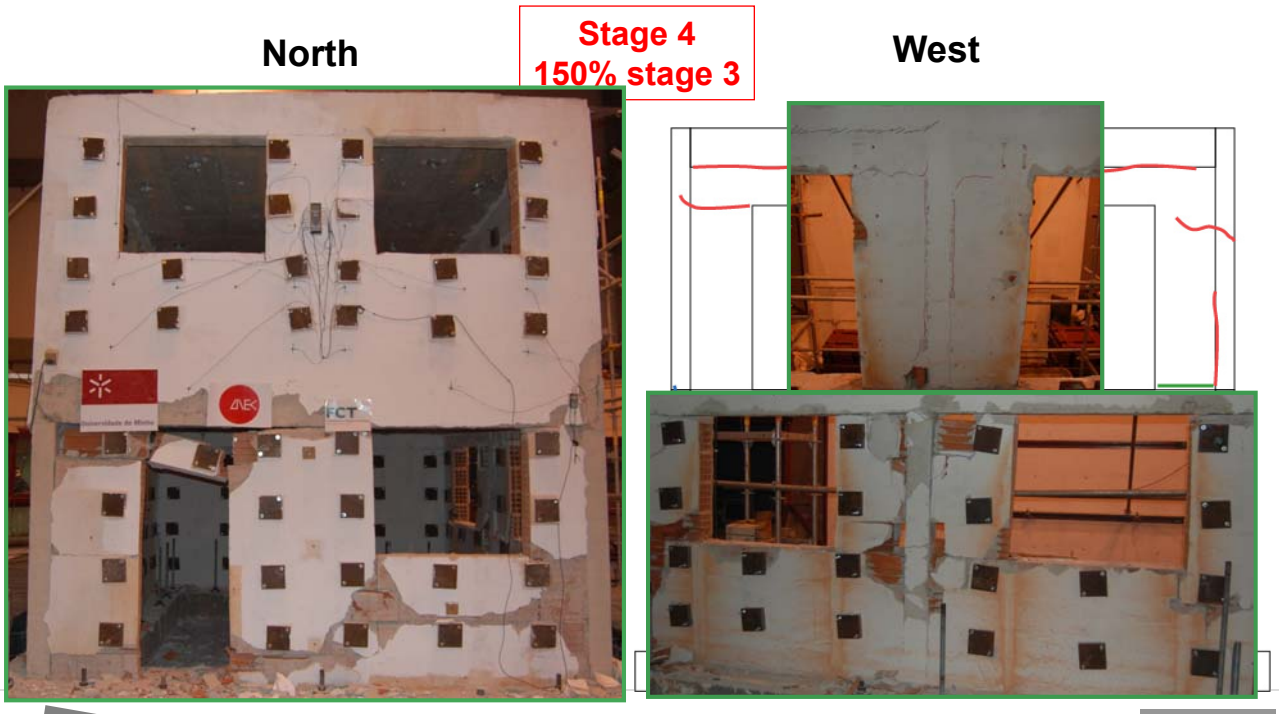






Results: Video of stage 4

Results: Cracking pattern and collapse mode of infill walls



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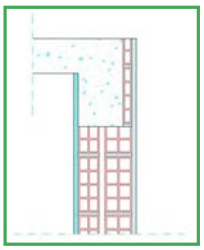
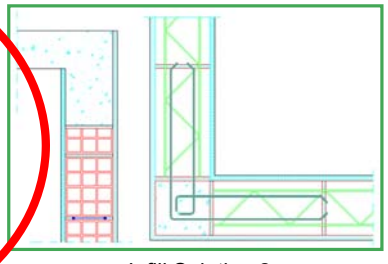
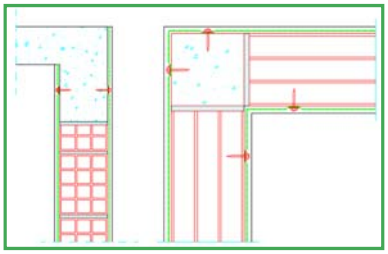


Infill Solution 1



Infill Solution 2



Infill Solution 3

Scope of the project: Shaking table experimental program

- Prototype reduced using Cauchy-Froud's Similarity Law to a scale of 1:1,5
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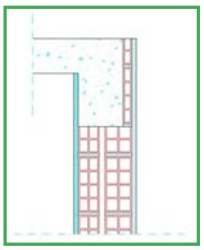
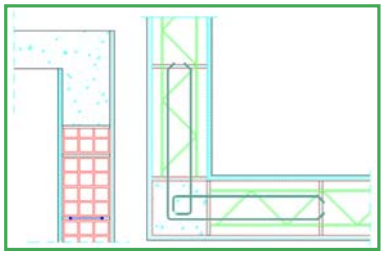
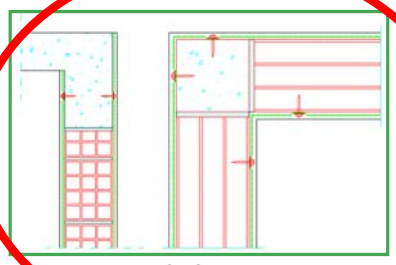
- One building represents what is built (unreinforced double leaf clay brick masonry infill and older standards) and the other two future possibilities (reinforced single leaf clay brick infill and Eurocodes)



Infill Solution 1

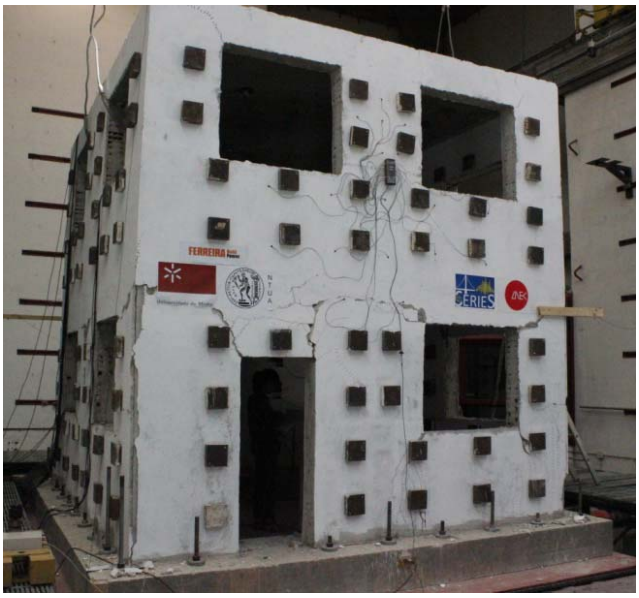


Infill Solution 2



Infill Solution 3

Results



Cracking in rendering around openings and corners

Results



Cracking in rendering around openings and corners

Results


Plaster removal: Toe and lintel crushing

Results

Separation between frame and infill

RC cracking (mid-height and joint)

Conclusions

- Rendering fell around the concrete frame, mainly at corners
- Out-of-plane expulsion of infills prevented due to bed joint reinforcement or steel net connected to the concrete frame
- The building, designed according to EC8 + reinforced infills, performed better than expected due to the masonry walls. No fragile collapses were found
- The building designed according to the Portuguese old code + unreinforced infills was able to perform better than expected due to the masonry walls. In the absence of reinforcement (or other), out-of-plane expulsion was found, with a unacceptable collapse mode of the buildings
- Few research exist on combined in-plane / out-of-plane. Demand is “unknown”. Capacity is almost unknown and the problem is ill conditioned. We are looking for design rules

Lessons #3

- Always connect the infills to the reinforced concrete frame (or find solutions to separate them and prevent out of plane failures)
- Dynamic results can be unexpected. Be ready to change (First test was made without openings in the infill. Final tests were made with openings and additional masses). Cauchy-Froude's similitude law required additional masses and a tedious addition of steel plates

Coming Up Tests

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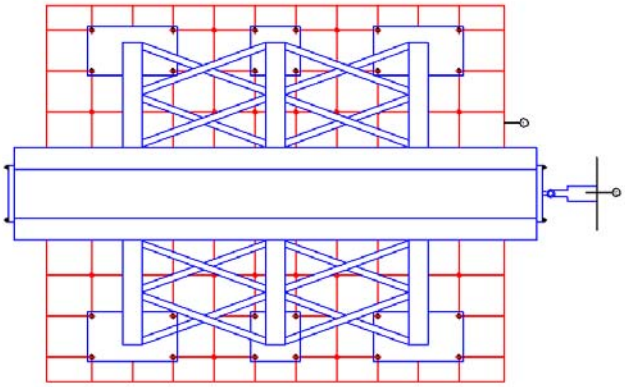
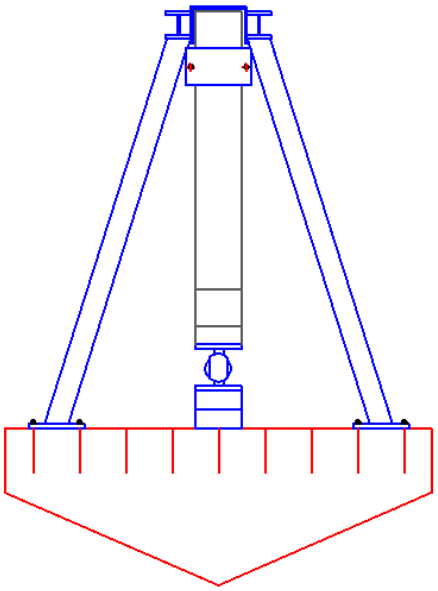
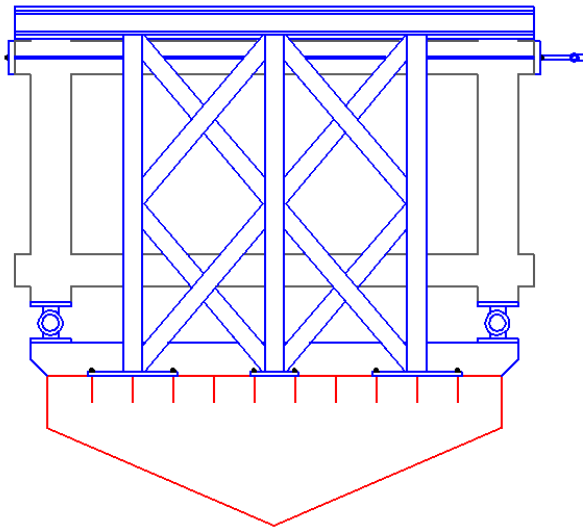
Masonry Infill Panels (I)







Masonry Infill Panels (II)

- Test masonry solutions from different parts of Europe
- Test innovative masonry solutions (infill separation and dry-stack)
- Test strengthened walls

National Technical University of Athens

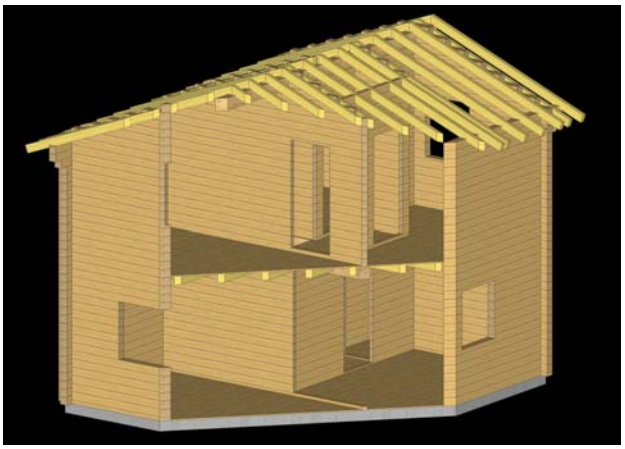
Università degli Studi di Pavia

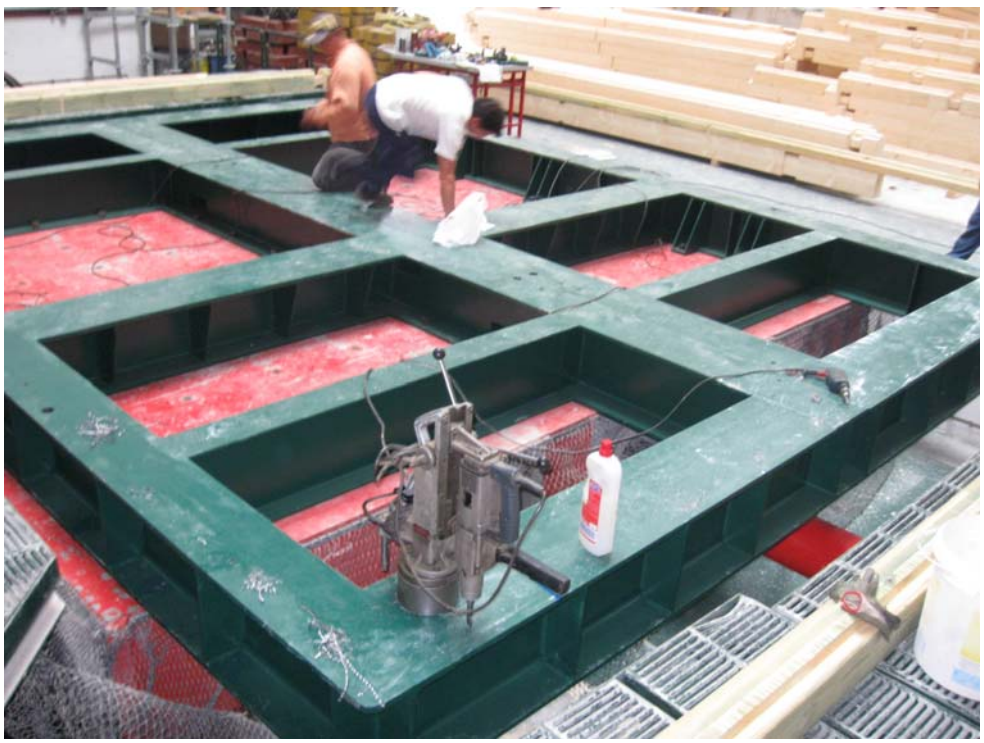
ZAG LJUBLJANA

Seismic performance of multi-storey timber buildings

Participants: University of Trento (Italy), University of Minho (Portugal), University of Graz (Austria), Piú Legno (Italy), Rubner (Italy), Rusticasa (Portugal), Mayr-Melnhof Kaufmann Gaishorn GmbH (Austria)

Construction system: Timber frame, log-house and cross-laminated timber



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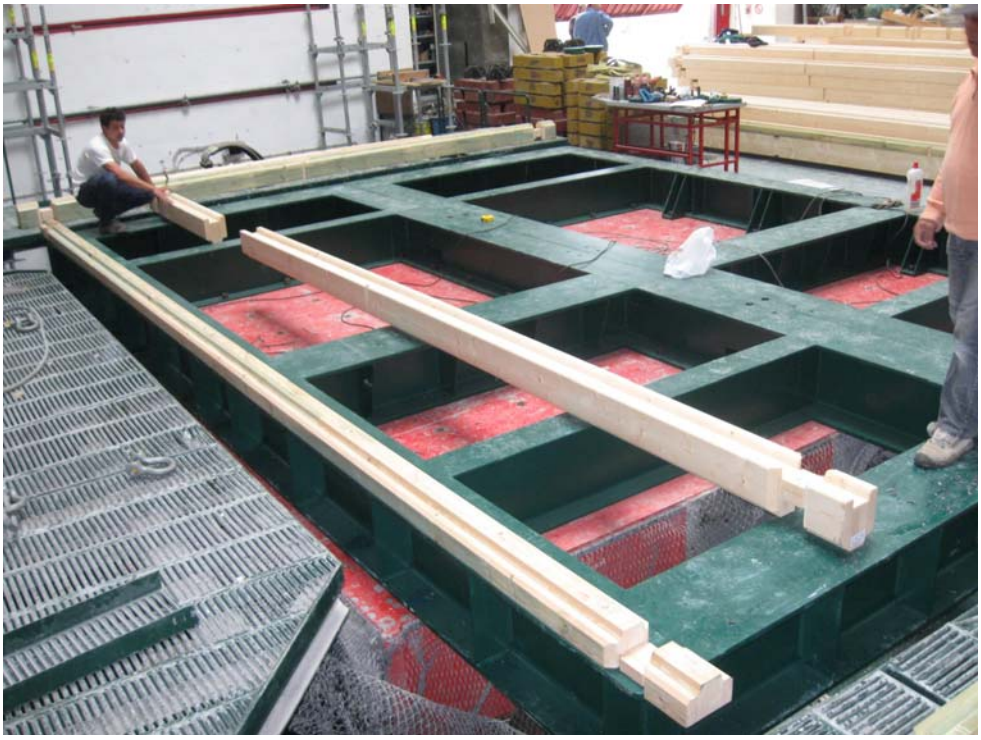

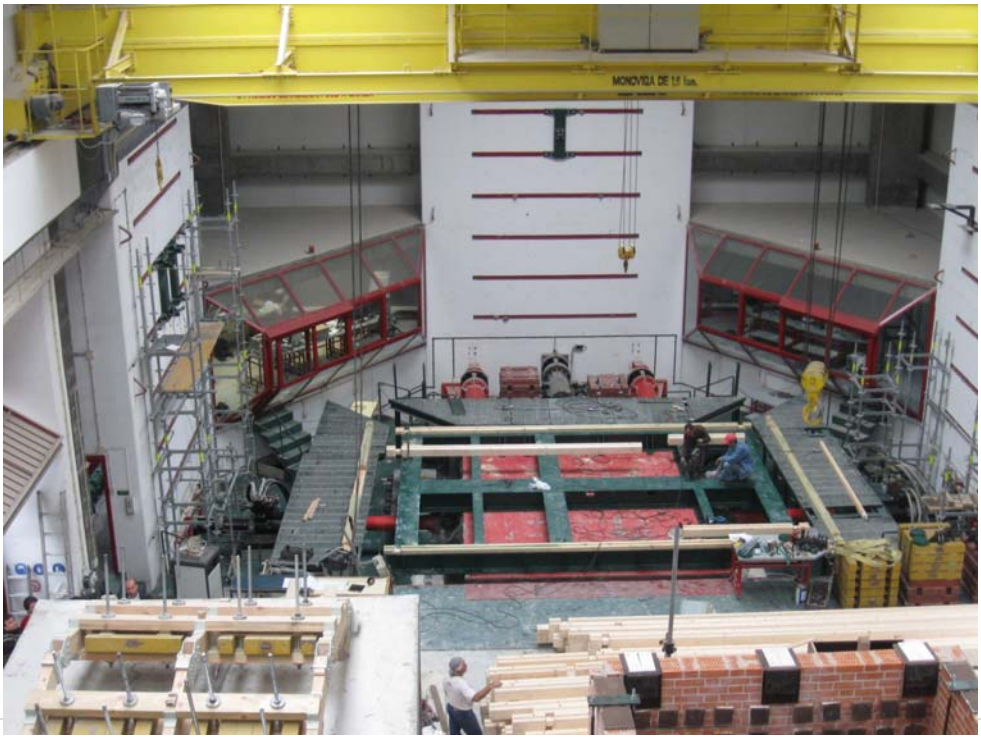

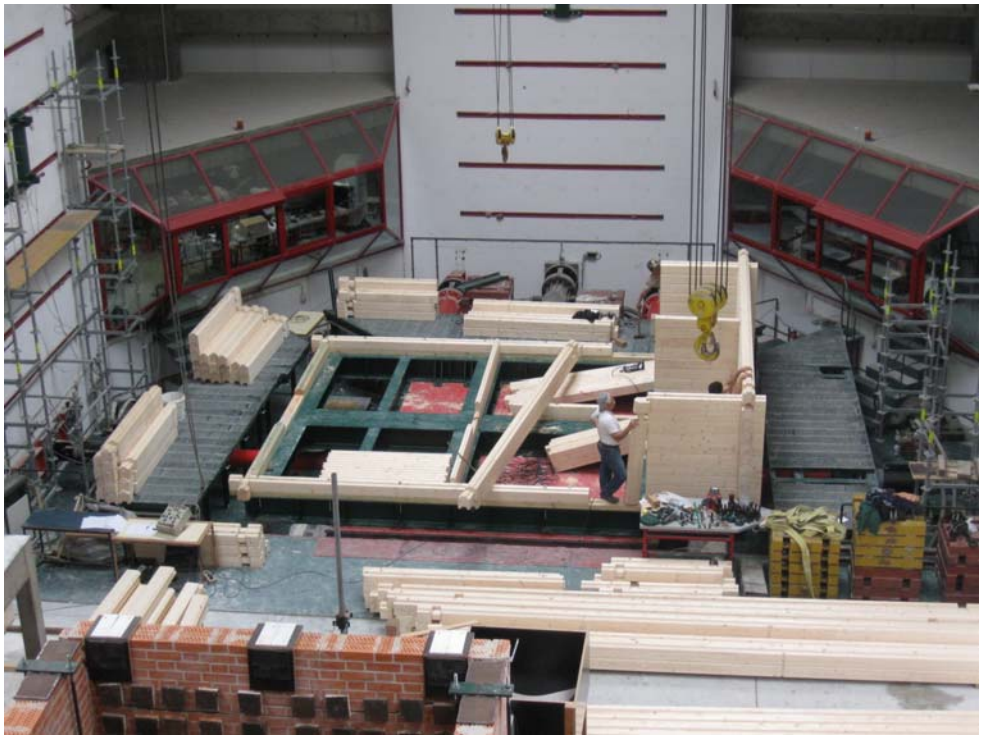


CARGAS SUSPENSAS
MONOVIGA DE 1,6 ton.


MONOVIGA DE 1,6 ton.


MONOVIGA DE 1,5 ton.


MONOVIGA DE 1,5 ton.


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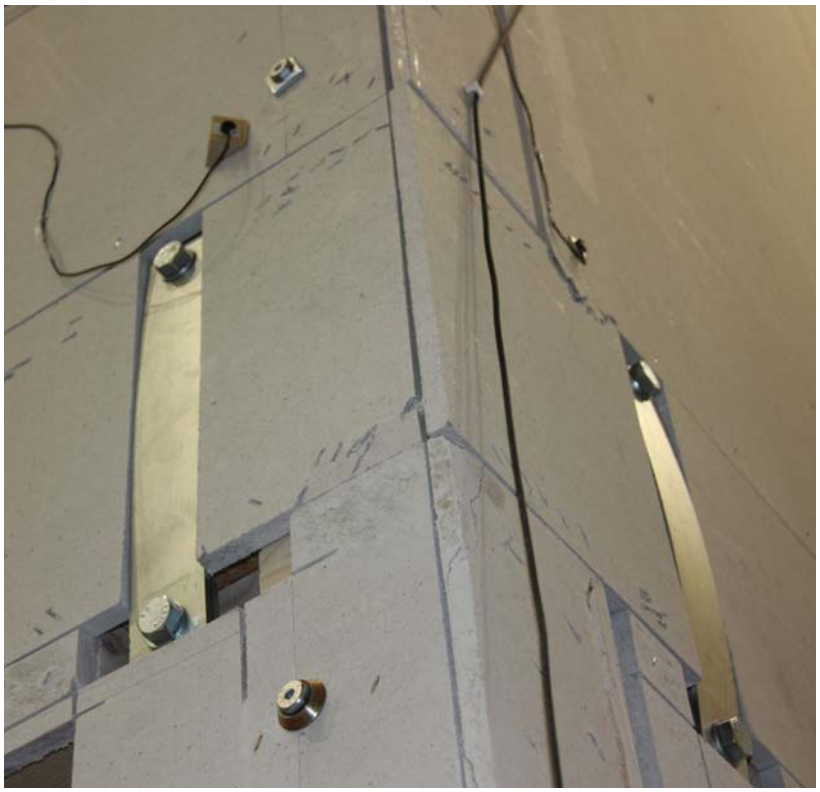
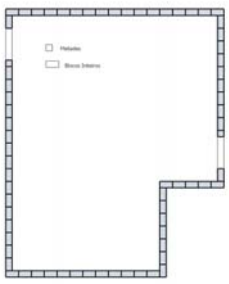
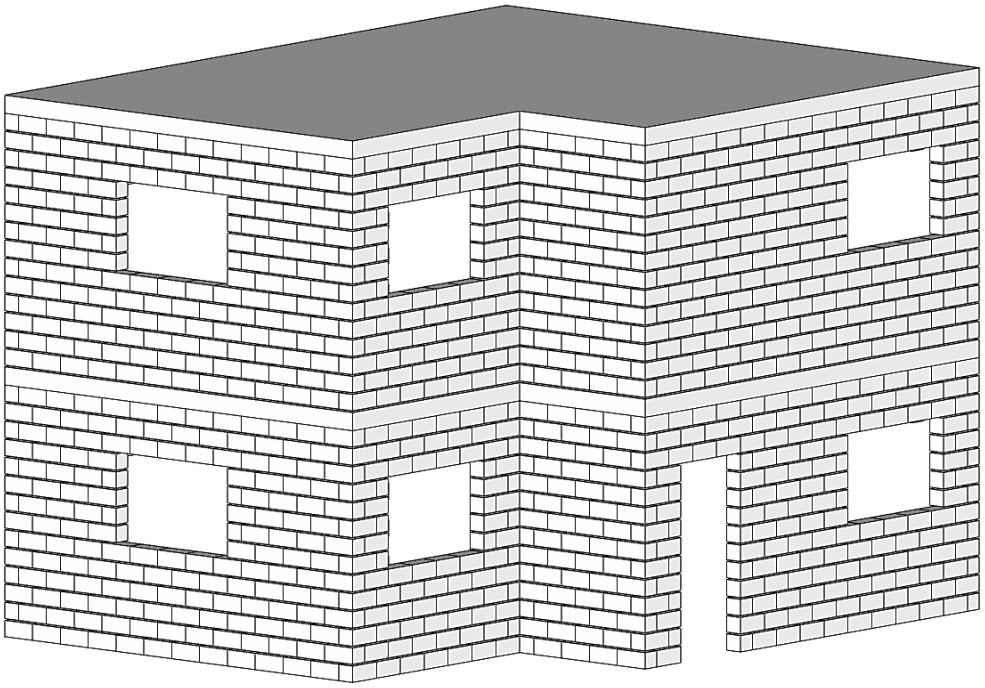
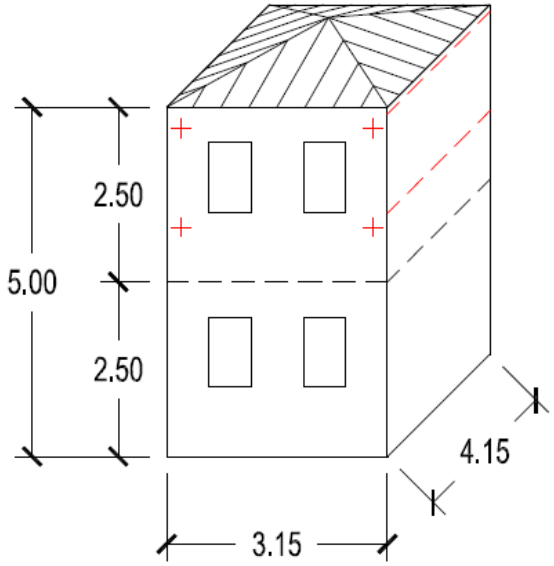


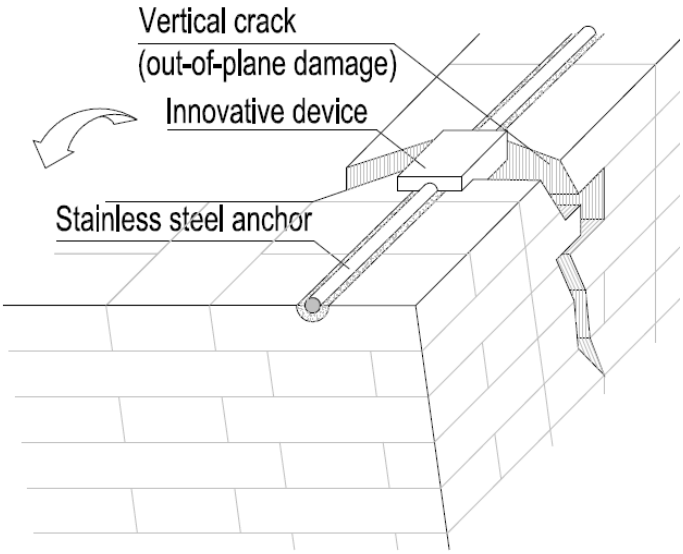
Larger Torsion Effects in Masonry (URM and Reinforced)





Dissipative Anchors





We are looking forward to more lessons…

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Universidade do Minho

Thank you for your attention