COORDINATOR:
UNIVERSITÀ DEGLI STUDI DI PADOVA

Structural Modeling of Historical Constructions

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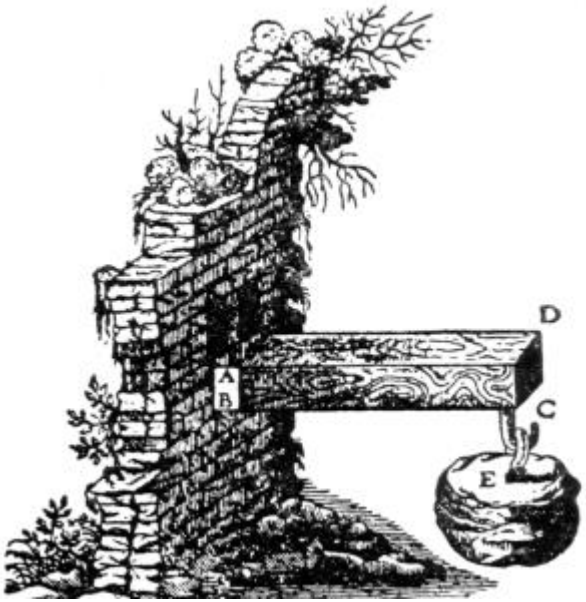
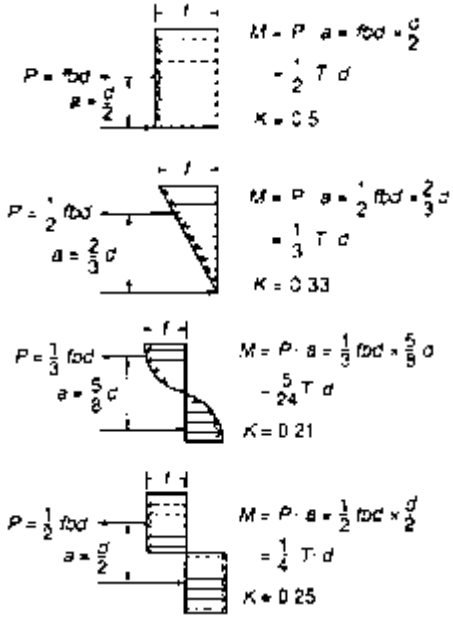
Contents

- NIKER
- What is Masonry?
- “Traditional” Approaches for Masonry Analysis
- Difficulties in practice
- Applications

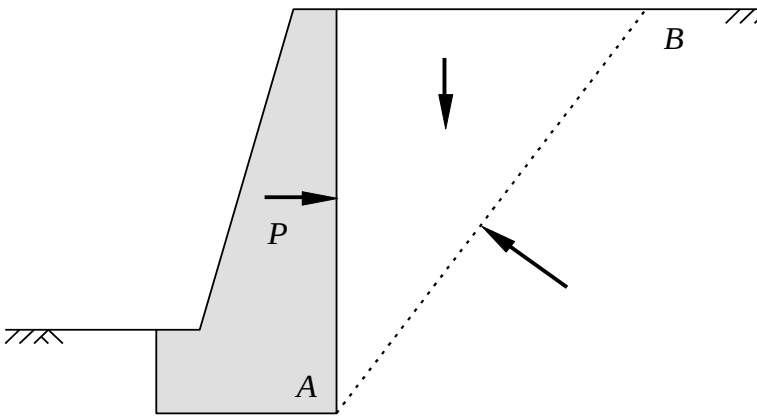
Linear elastic analysis?

- "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?

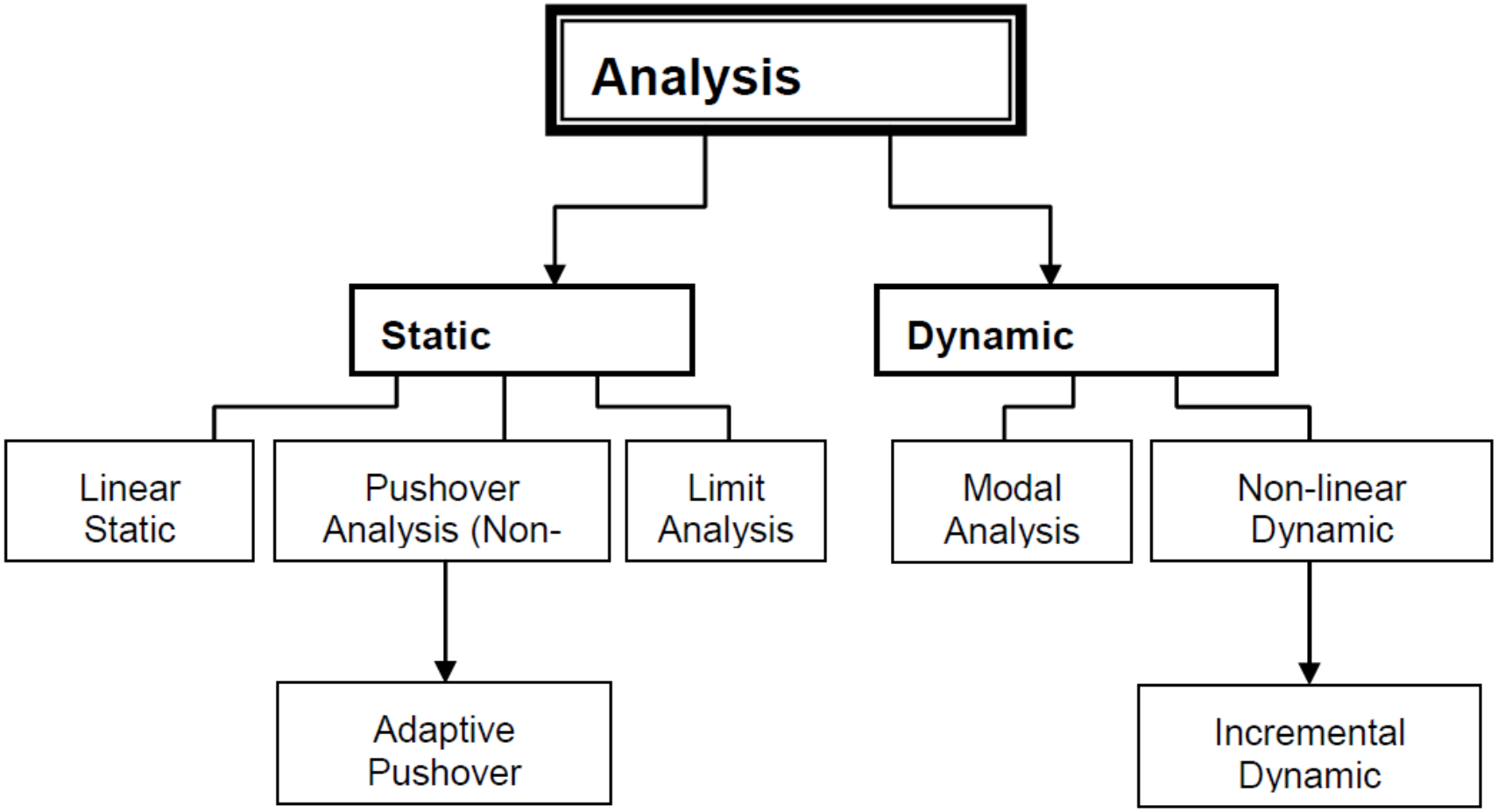
- Structural collapse does not generally coincide with the appearance of the first crack or localized early crushing → elasticity theory is a step back with respect to limit analysis?

- 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

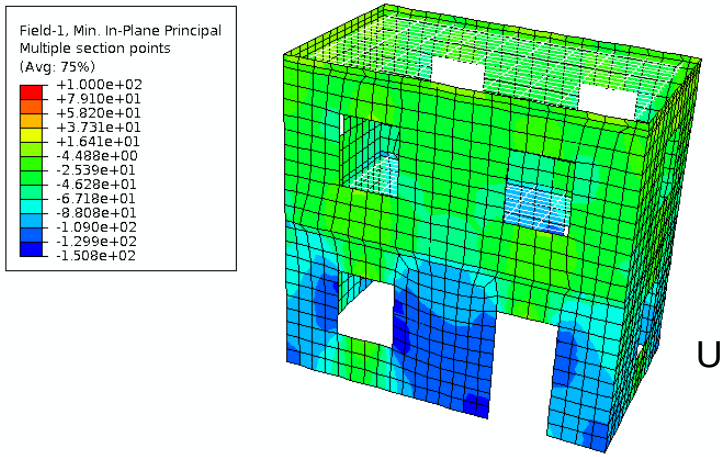
Analysis Methods



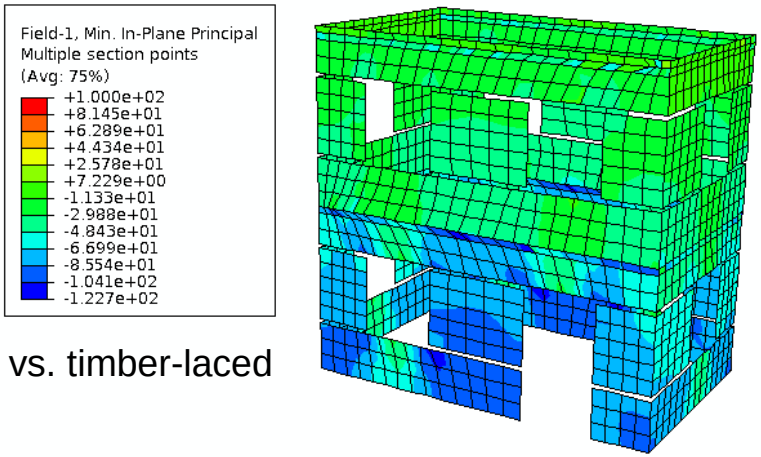
NIKER Deliverables

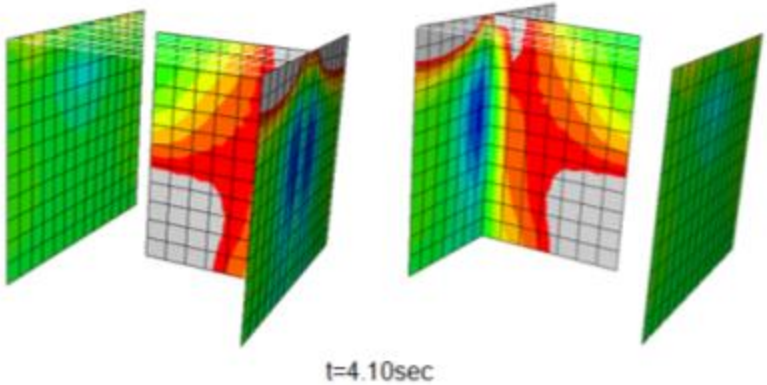
- Simplified and complex models of in- and out-of-plane response to be implemented in global analyses
- Development of reliable numerical models and assessment of connections and substructures
- Parametric study of buildings according to geometry, intervention techniques, stiffness of horizontal elements, connections
- Reliably quantification of building performance and response parameters for use in seismic assessment and design

Development of reliable numerical models and assessment of connections and substructures: Connections

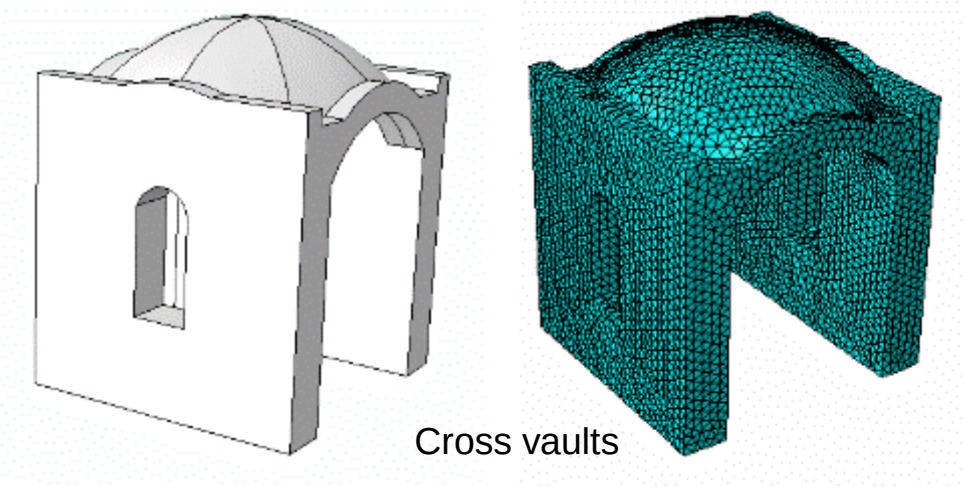


Unstrengthened vs. timber-laced



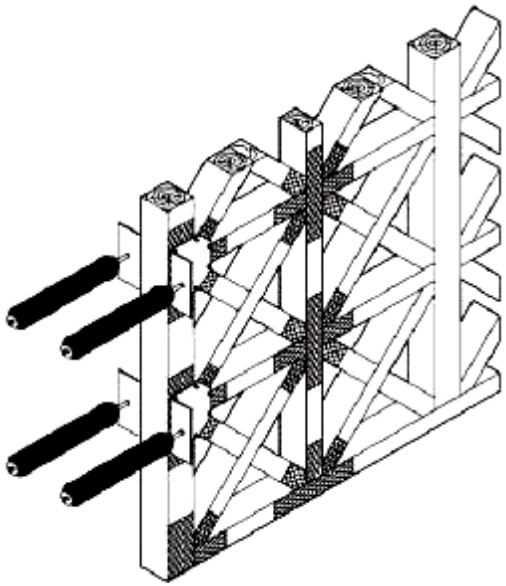


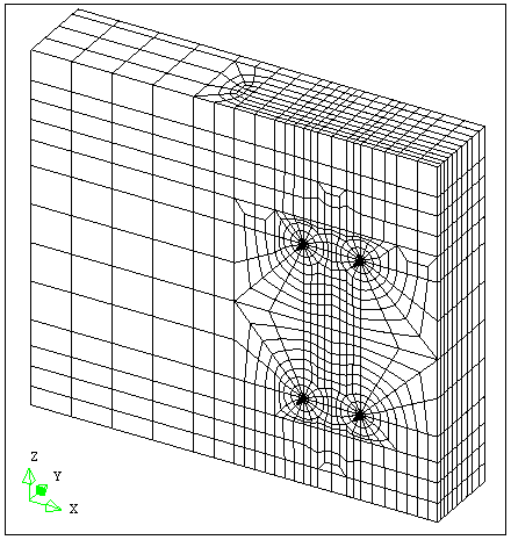
T-Structure masonry wall

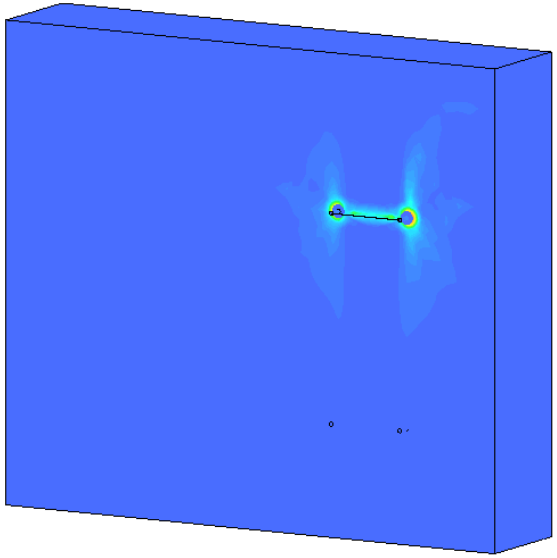


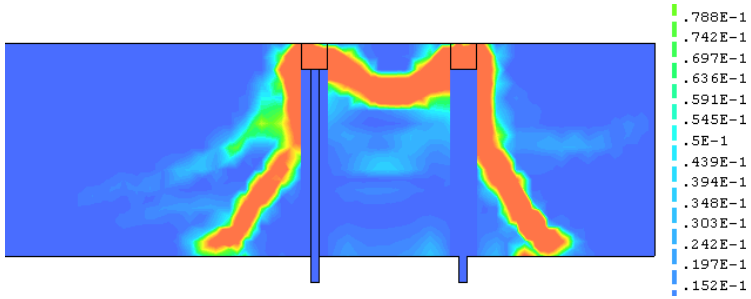
Cross vaults

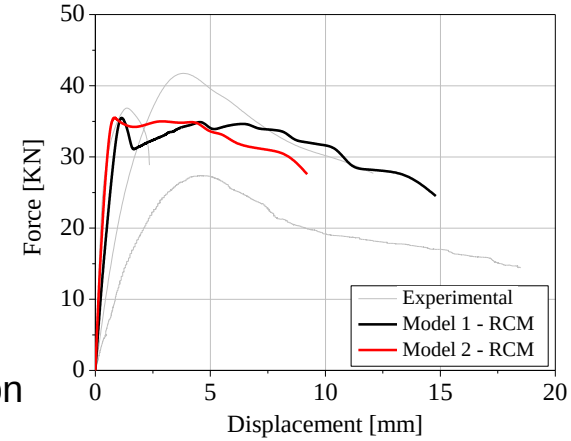
Development of reliable numerical models and assessment of connections and substructures: Wall to wall connections





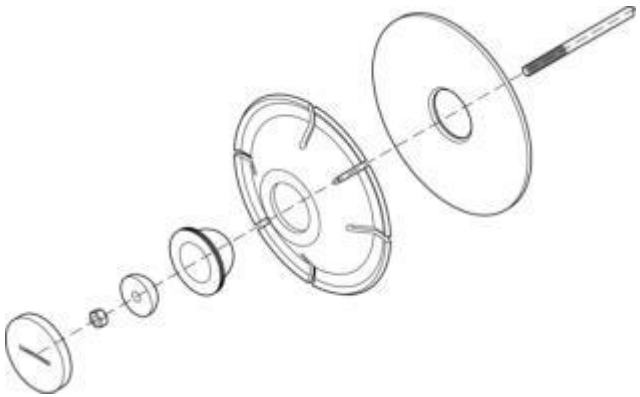


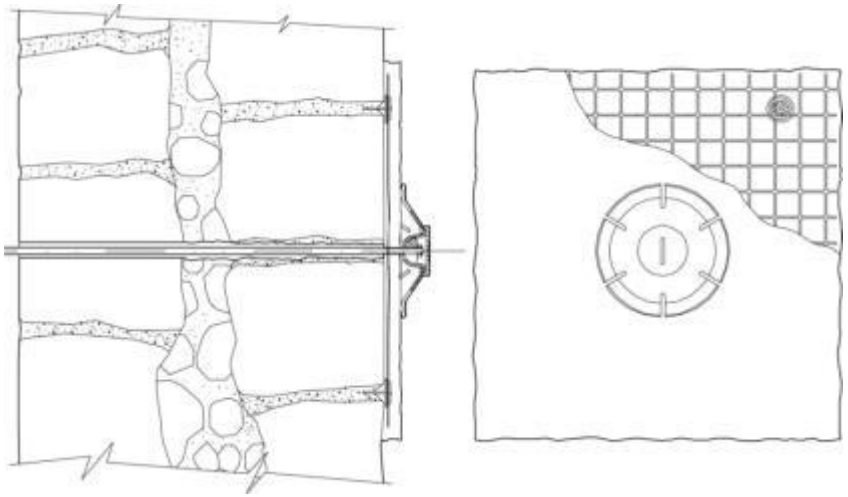


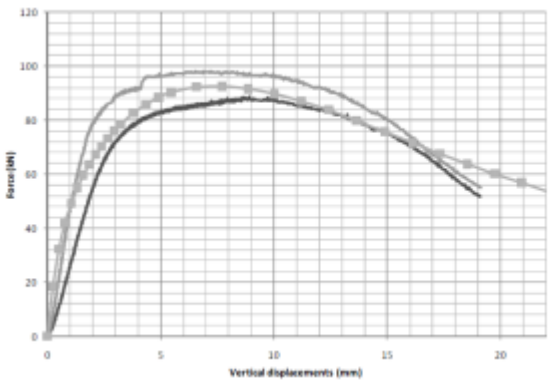


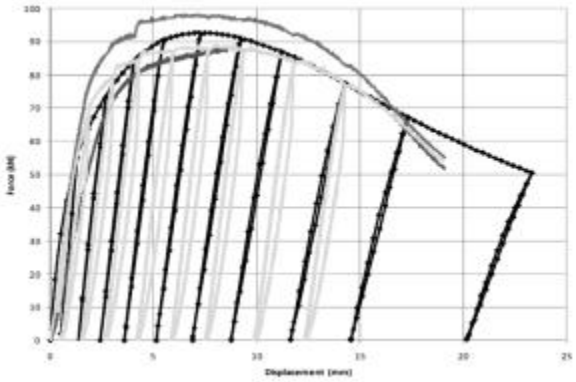
Validation

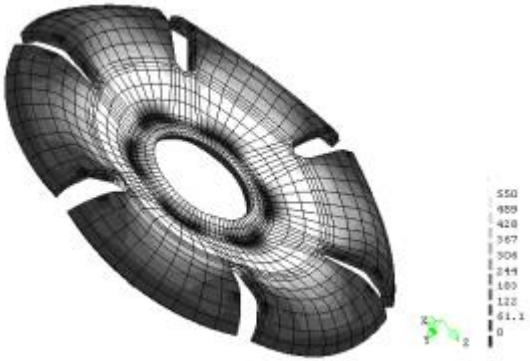
Development of reliable numerical models and assessment of connections and substructures: Dissipative connections





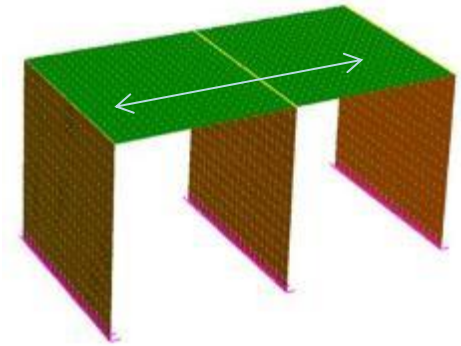




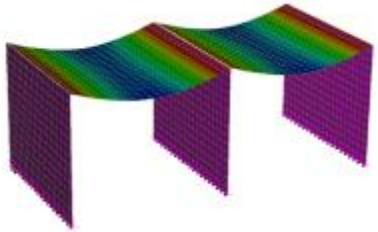


Validation

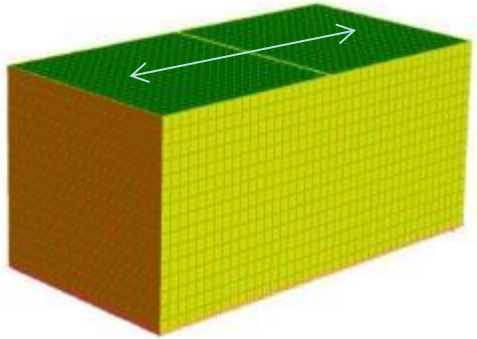
Parametric study of buildings: Floor stiffness



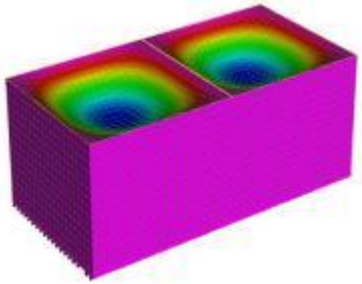
M1: unidirectional floor simply supported to the shear walls



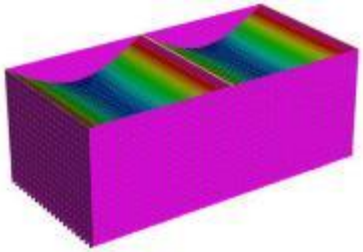
Walls are 3 m high, 4 m long and 50 cm thick, and equally spanned at 3.5 m



M2: bidirectional floor (slab) simply supported in a box-like wall structure



M3: unidirectional floor in a box-like wall structure simply supported to the shear walls



Parametric study of buildings: Material properties

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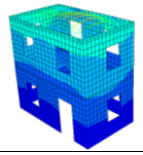
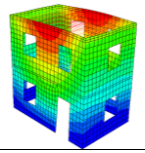
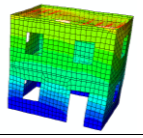
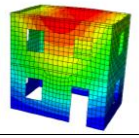
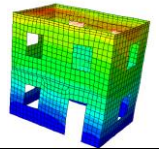
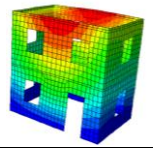
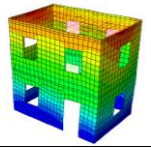
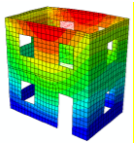
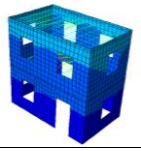
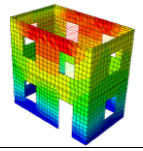
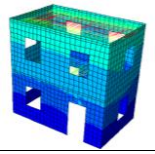
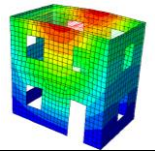
reference	-		6.58		4.87
Profile of joists	8x10cm^2		6.75		4.94
Profile of planks	1.5x10cm^2		6.70		4.95
	2.0x10cm^2		6.88		5.07
Properties of wooden elements	C24 E=11GPa G=0.69GPa		8.18		6.10
Properties of masonry walls	ρ=2.30Mgr/m^3 E=1.4GPa		9.41		7.57

UNREINFORCED MODEL

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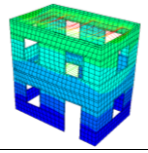
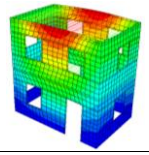
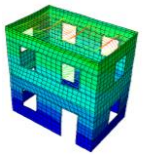
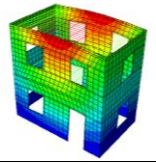
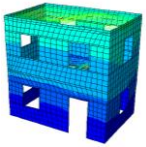
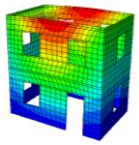
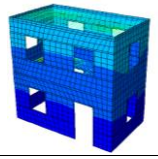
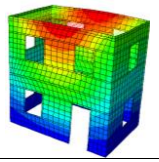
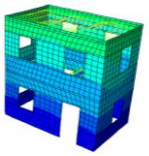
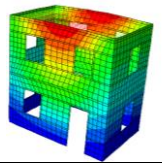
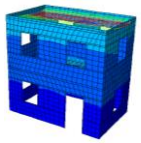
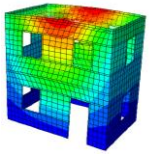
reference	-		8.58		6.61
Profile of joists	8x10cm^2		9.10		6.70
Profile of planks	1.5x10cm^2		8.94		6.72
	2.0x10cm^2		9.18		6.78
Properties of wooden elements	C24 E=11GPa G=0.69GPa		8.98		6.81
Properties of masonry walls	ρ=2.30 Mgr/m^3 E=1.4GPa		10.16		9.10

TIMBER LACED MODEL

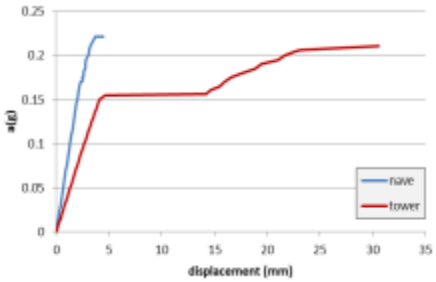
Parametric study of buildings: Material properties

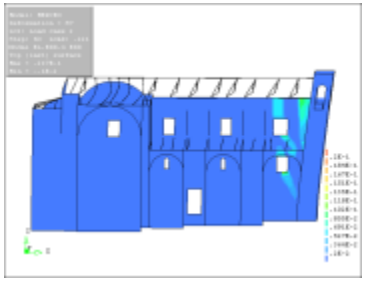
	Lower value	Reference value	Upper value
Young's modulus of the walls	$0.5x E_{walls,ref}$	$E_{walls,ref}$ = 1.00 GPa	$2.0x E_{walls,ref}$
Young's modulus of the floors	$0.1x E_{floors,ref}$	$E_{floors,ref}$ = 0.16 GPa	$10x E_{floors,ref}$
Compressive strength	$0.5x f_{c,ref}$	$f_{c,ref}$ = 1.00 MPa	$2.0x f_{c,ref}$
Compressive fracture energy	$0.5x G_{c,ref}$	$G_{c,ref}$ = 1.00 N/mm	$2.0x G_{c,ref}$
Tensile strength	$0.5x f_{t,ref}$	$f_{t,ref}$ = 0.10 MPa	$2.0x f_{t,ref}$
Tensile fracture energy	$0.5x G_{t,ref}$	$G_{t,ref}$ = 0.05 N/mm	$2.0x G_{t,ref}$

Load pattern	displacement proportional to the first mode

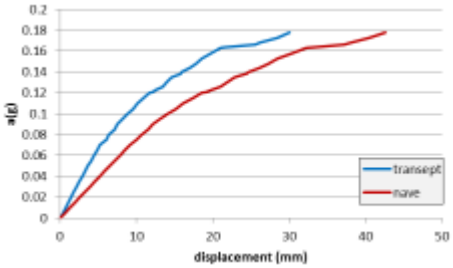
Parametric study of buildings: Connections

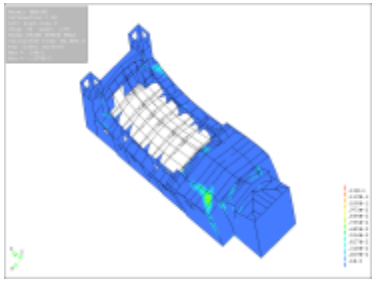
Reference model





X direction





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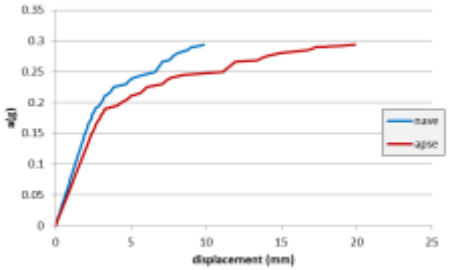
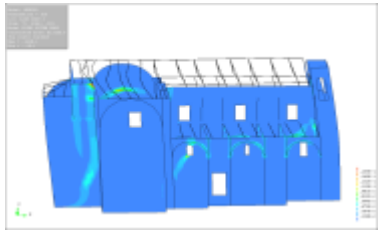
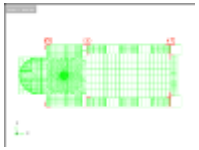


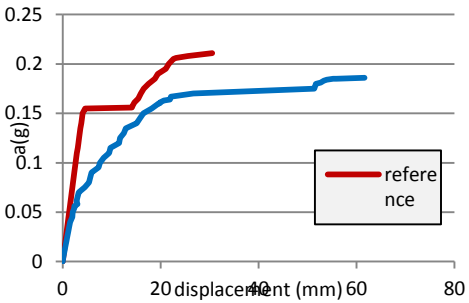


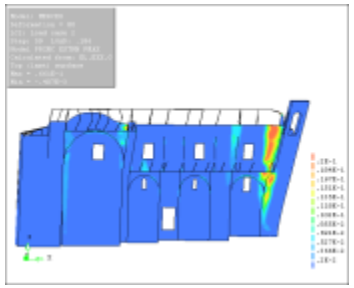
-X direction

Parametric study of buildings: Connections

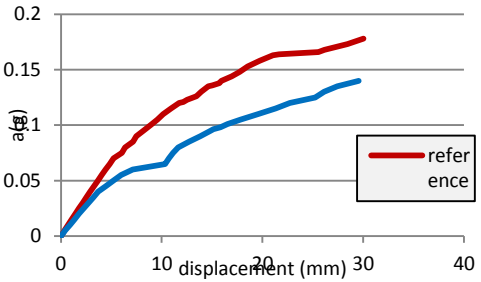
Weakened Connections

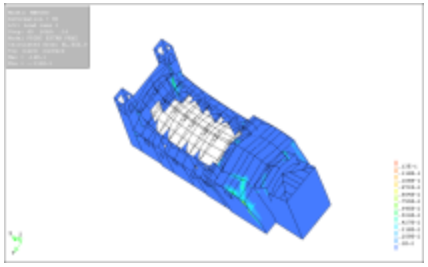




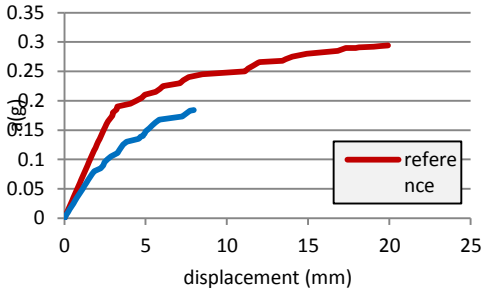


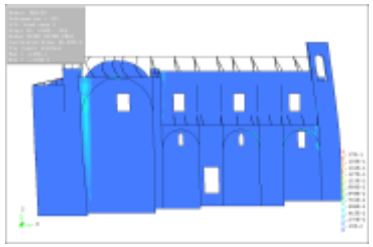
X direction





Y direction

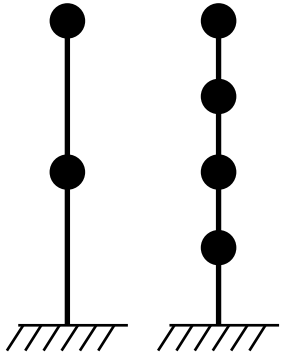




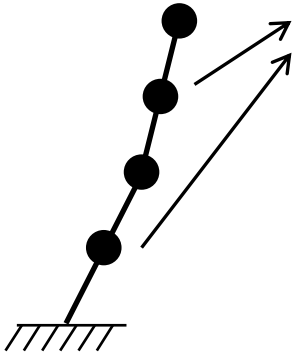
Reliable seismic assessment: Displacement based design

Real Structure

2 DoF 4 DoF

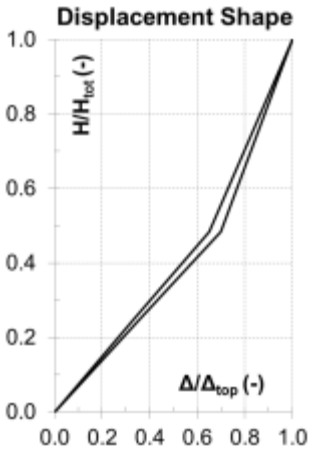


Displacement Shape



middle-storey DoFs showed displacements that can be consider linear with those at storey levels:

- Schematization with 2 DoF is enough accurate
- Displacement shape can be identified by normalized displacement at first floor (Δ_{FF}/Δ_{top})



Results of dynamic analyses:

- Both the directions
- For the several levels of PGA

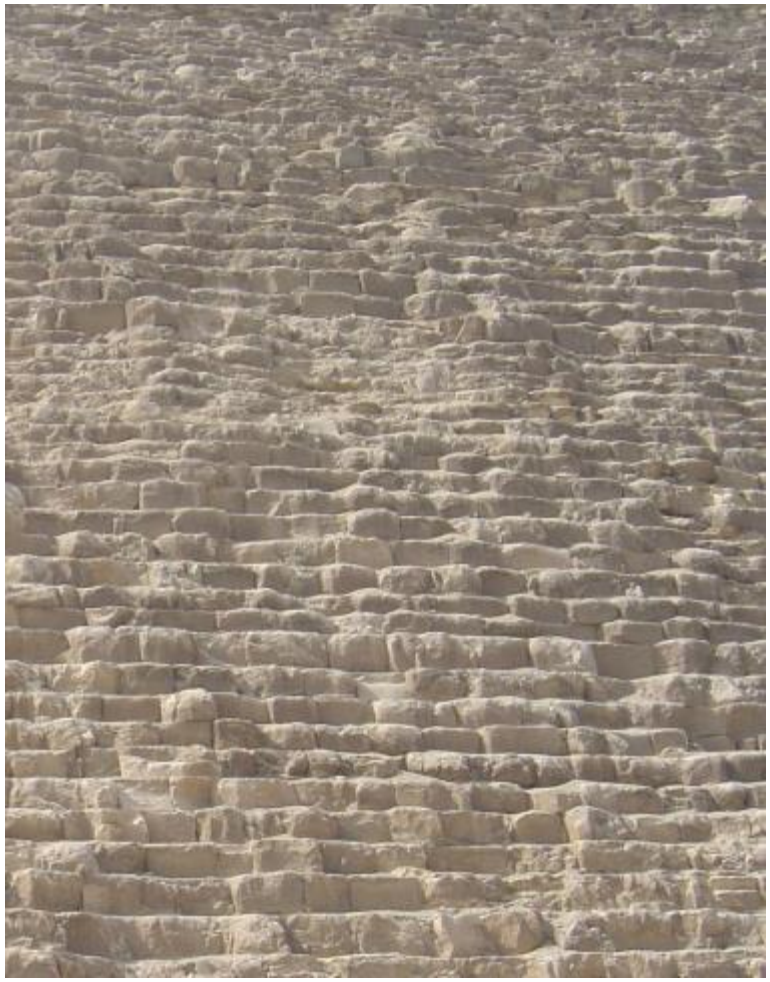
↓

$\Delta_{FF}/\Delta_{top} \approx 0.65 \div 0.70$ ⟶

- Effective Height ≈ 0.7 H_{tot}
- Effective Mass ≈ 0.8 M_{tot}

WHAT IS MASONRY?

What is masonry?



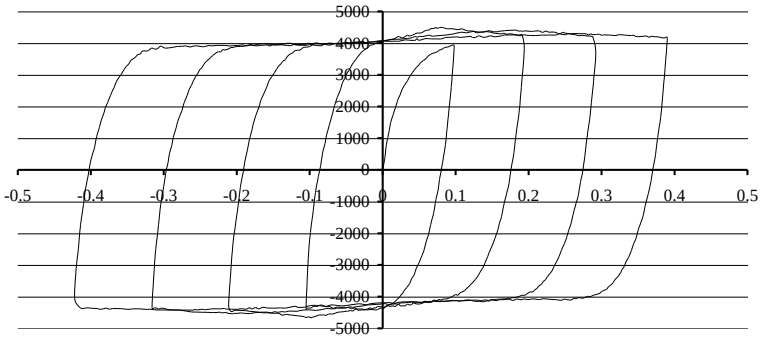
What is masonry?

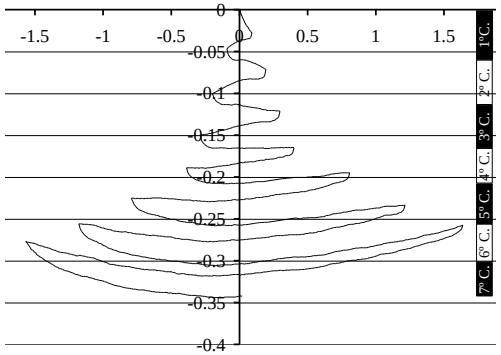
Masonry can be defined as a material with visible internal structure

Why is this relevant for mechanics?

Shear testing of stone joints

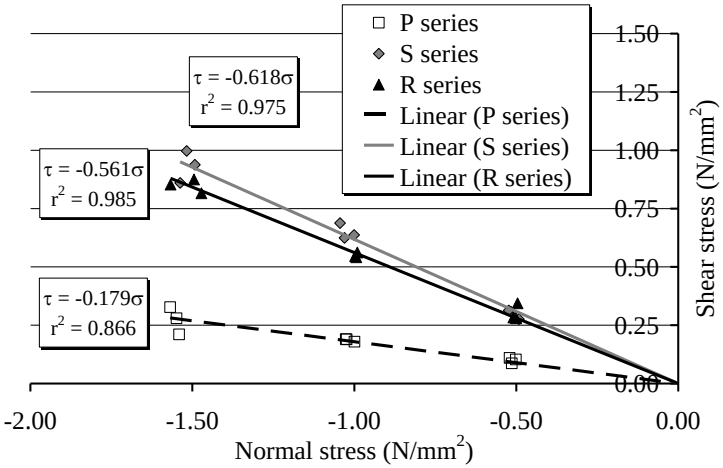
Stress-strain relation



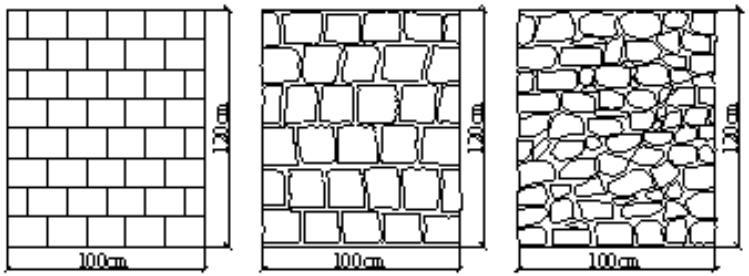


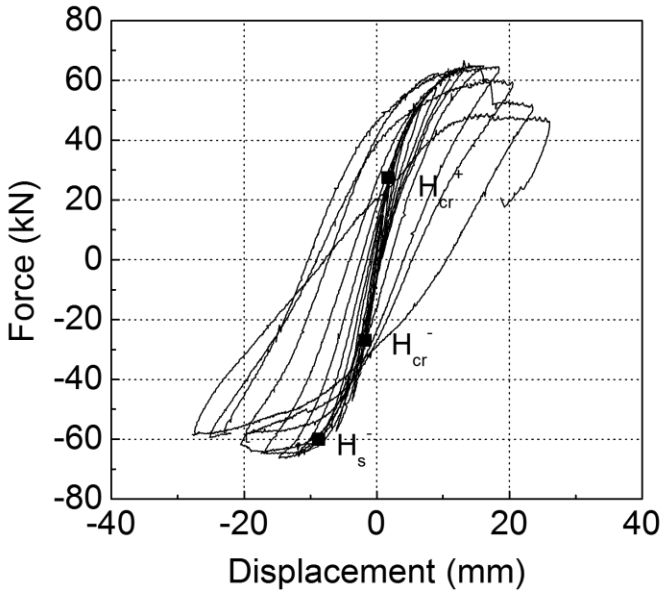
Dilatancy

Failure surface



Why is this relevant for mechanics?



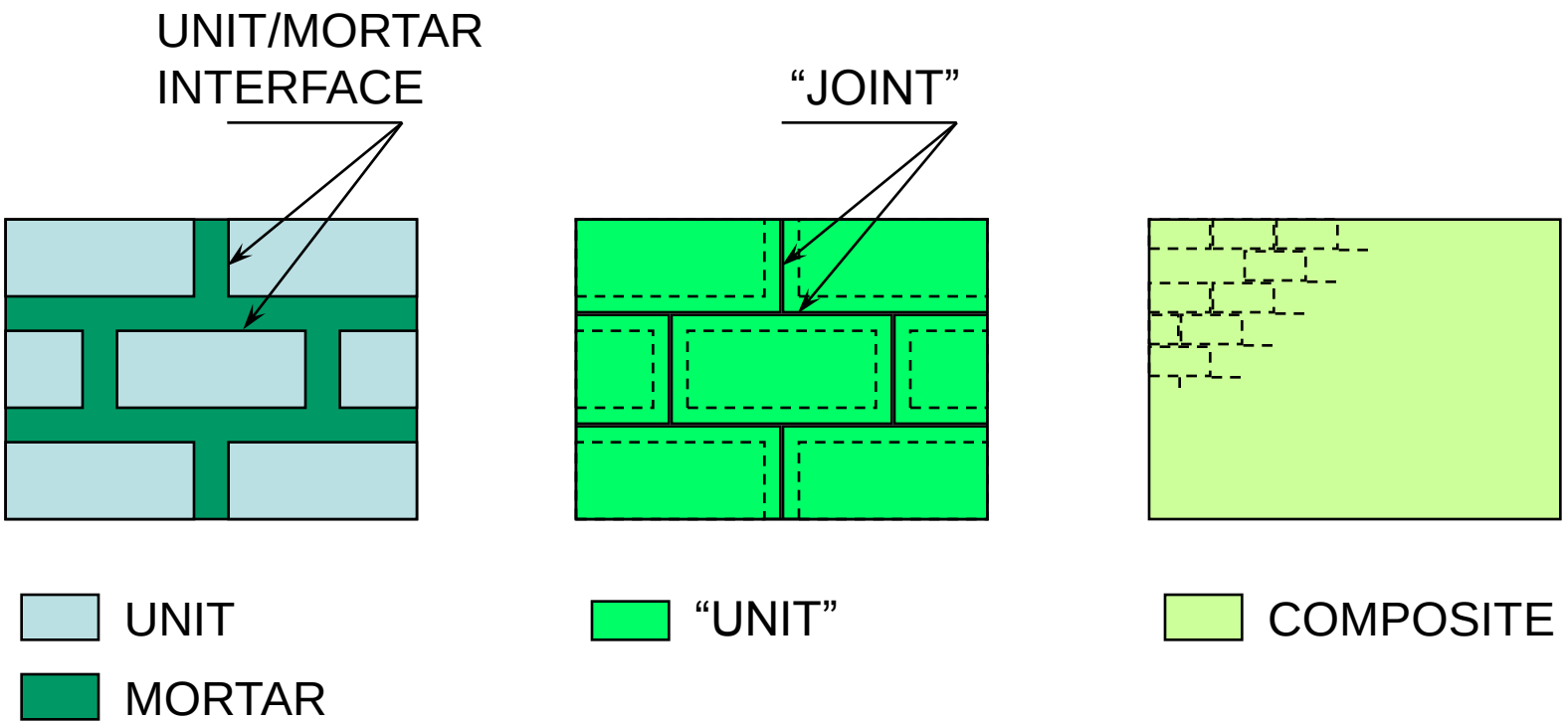


Stone walls

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

“TRADITIONAL” APPROACHES FOR MASONRY ANALYSIS

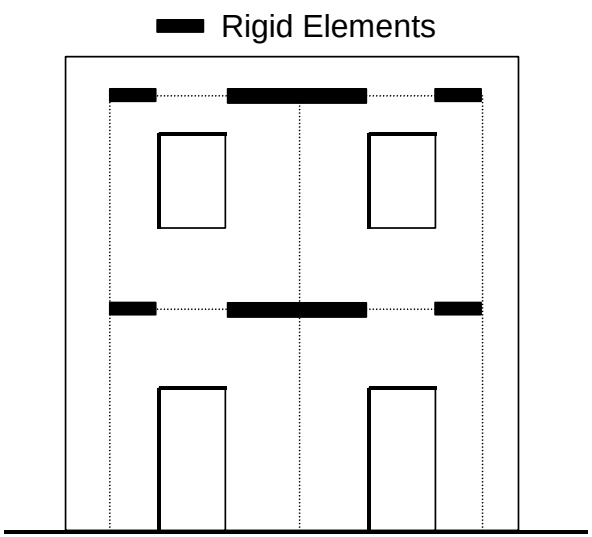
Modeling masonry – Material Level



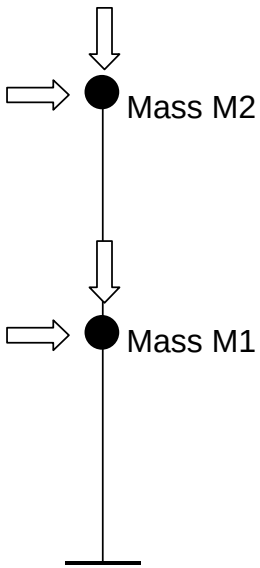
MASONRY SAMPLE **MICRO-MODELING** **MACRO-MODELING**

Sophisticated models require advanced material characterization. Much experience had been gained in the last decade

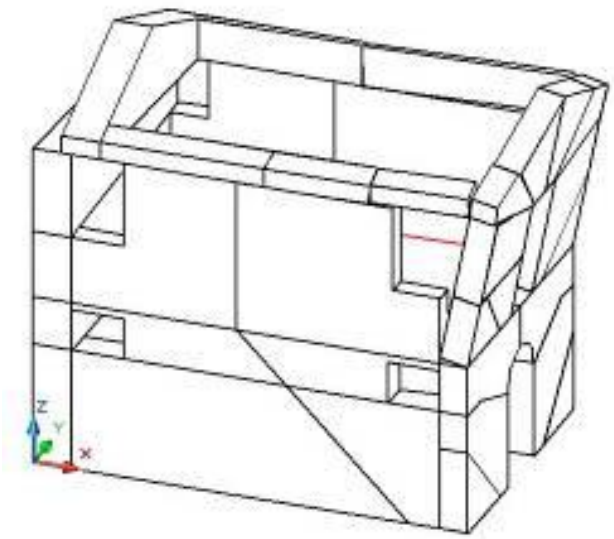
Modeling Approaches – Structural Level (I)



Beam elements model



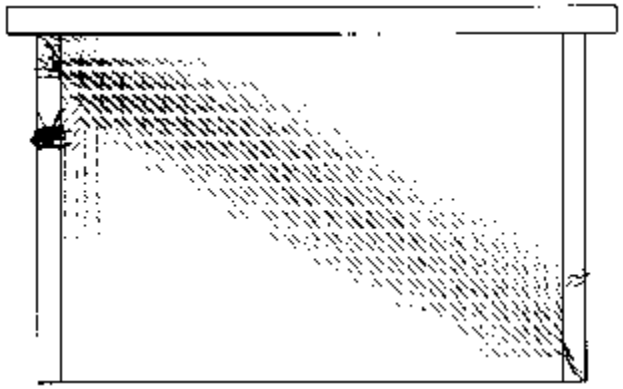
3-degree of freedom model



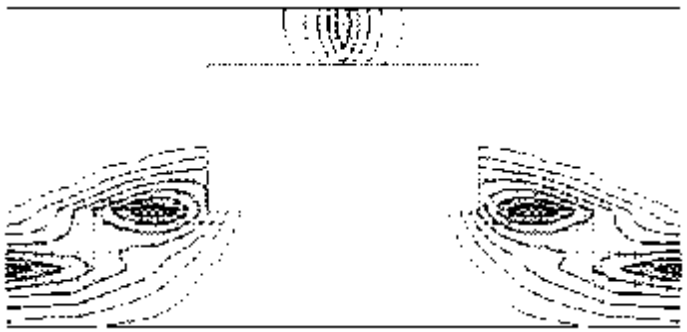
Macro-block model

STRUCTURAL COMPONENT MODELS

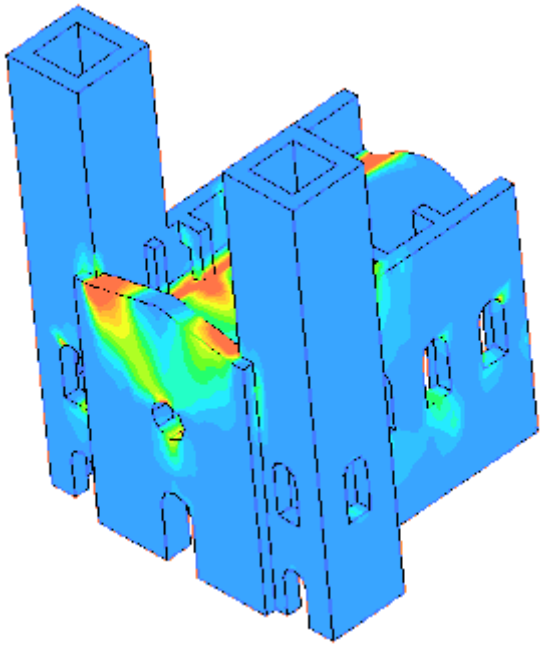
Modeling Approaches – Structural Level (II)



Shear wall



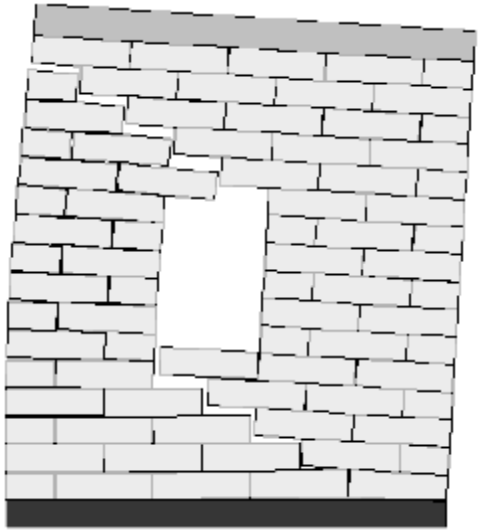
Wall with out of plane behavior



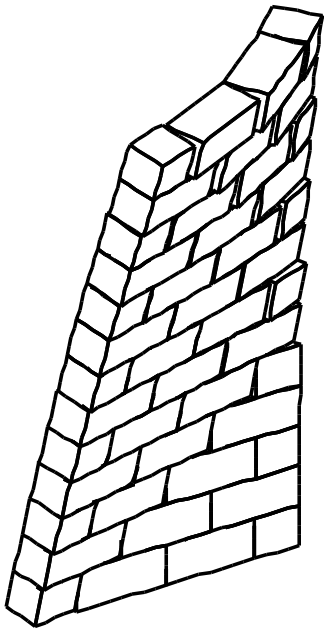
Church Settlements

STRUCTURAL MACRO-MODELING / FINITE ELEMENT METHOD

Modeling Approaches – Structural Level (III)



Shear wall
(in plane behavior)

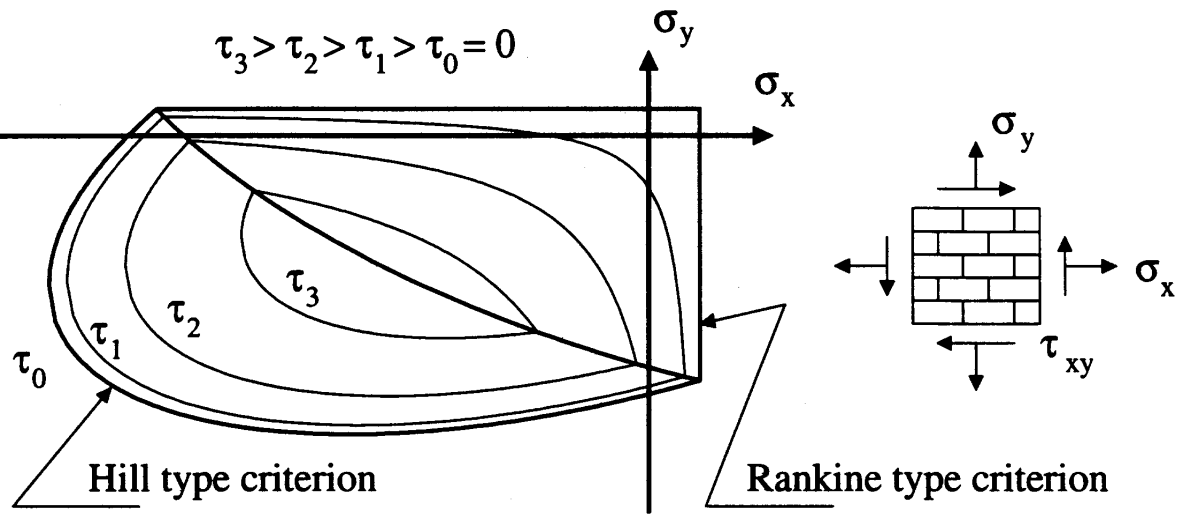


Wall with
out of plane behavior

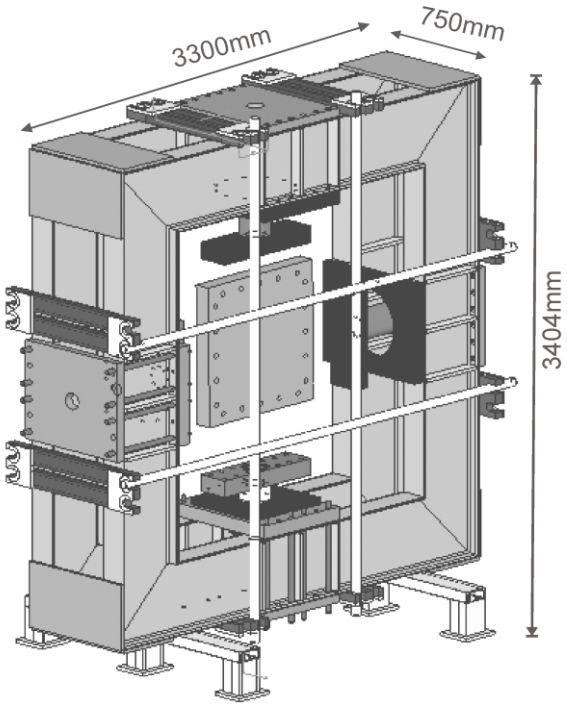
STRUCTURAL MICRO-MODELING / FEM, DEM, LIMIT ANALYSIS

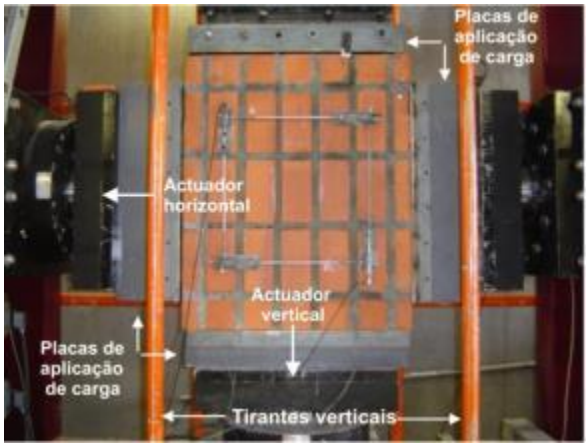
HOMOGENIZATION TECHNIQUES

HOMOGENISATION
(or from micro- to macro-modeling)



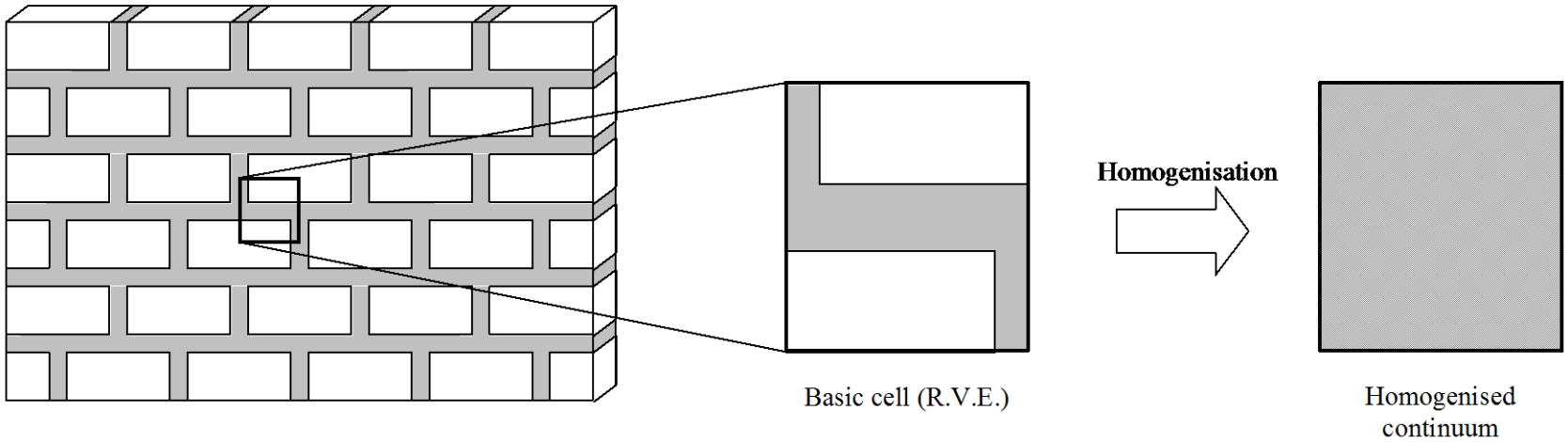
Masonry Anisotropy





Biaxial Testing

HOMOGENISATION (or from micro- to macro-modeling)

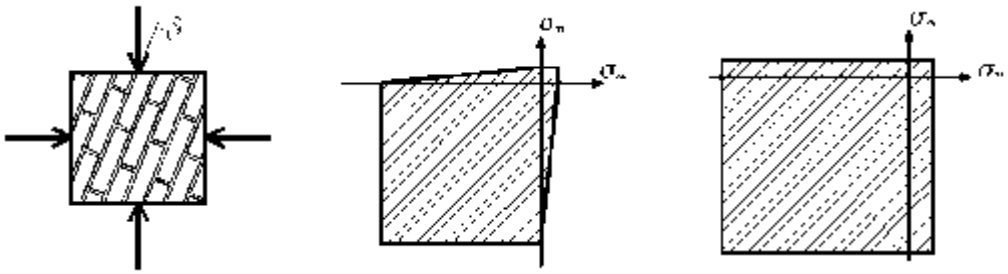


Homogenization Process

The failure surface of the structure is normally not known, but only calculated for each stress path.

MULTI-PATH SOLUTION AND COMPARISION OF HOMOGENISED COLUTION WITH EXPERIMENTAL RESULTS (PAGE 1981)

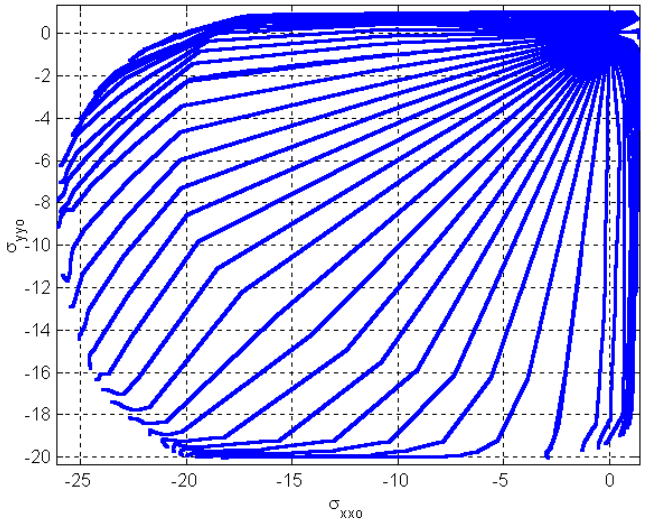
1) Failure surface units: Rankine (f_t=0.1 N/mm^2 f_c/f_t=20)
2) Failure surface mortar: Mohr Coulomb (f_t=0.15 N/mm^2 f_c/f_t=15)

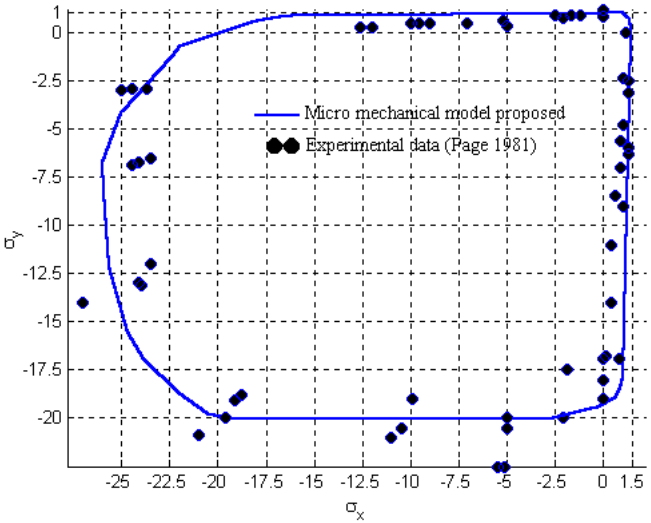


e_v=1.5

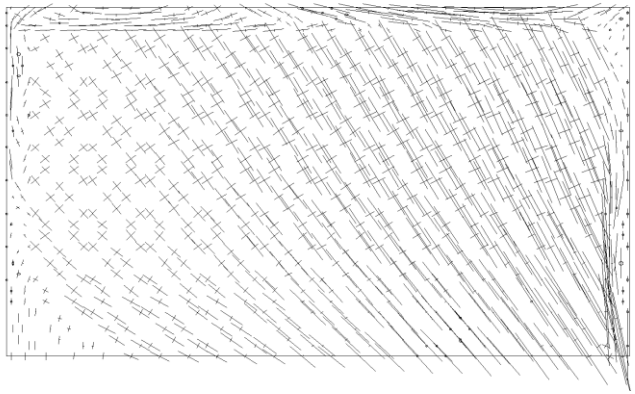
e_h=1.5

b=3.3a

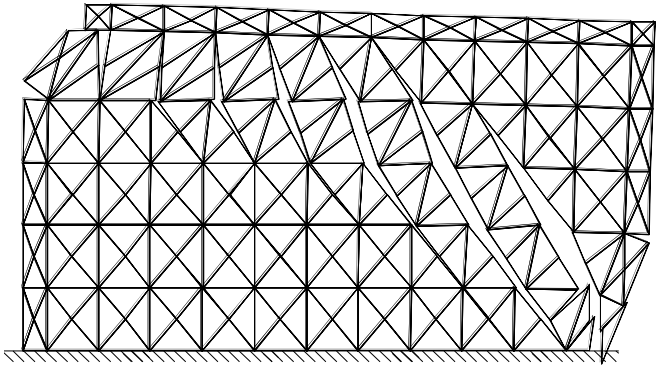




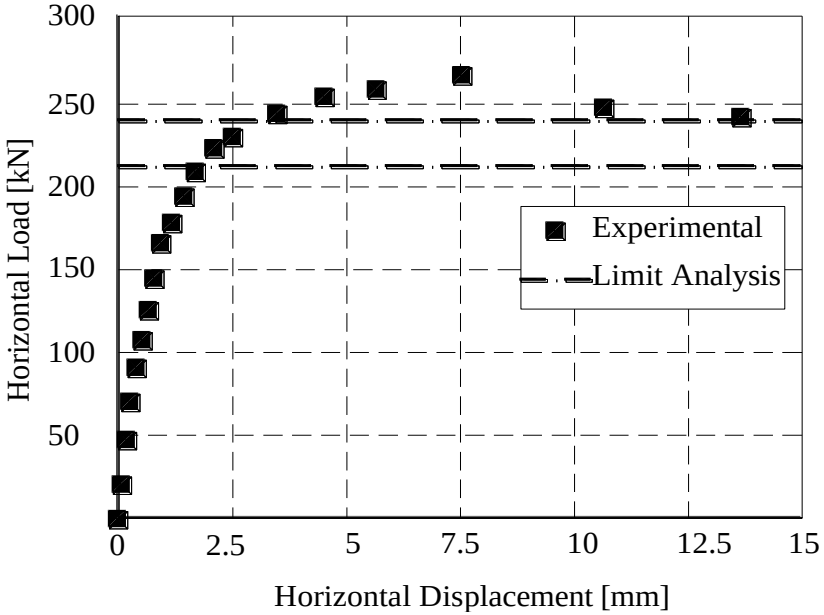
LIMIT ANALYSIS HOMOGENIZATION APPROACH



Lower Bound

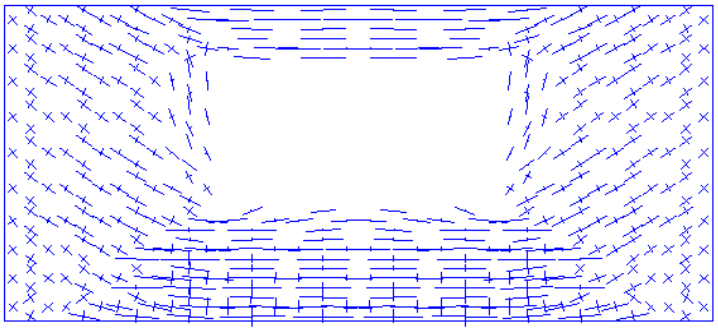


Upper Bound

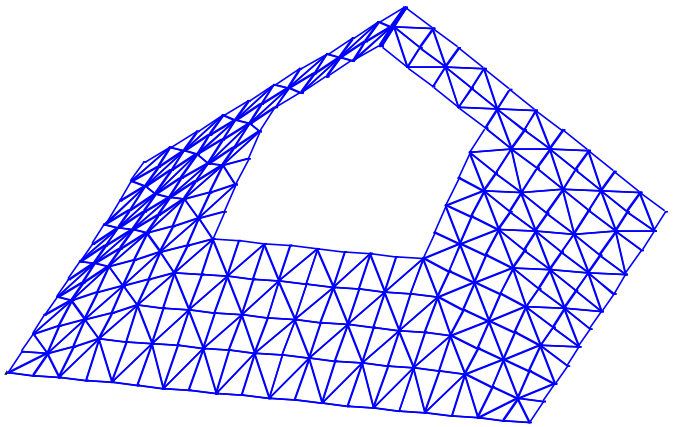


Results

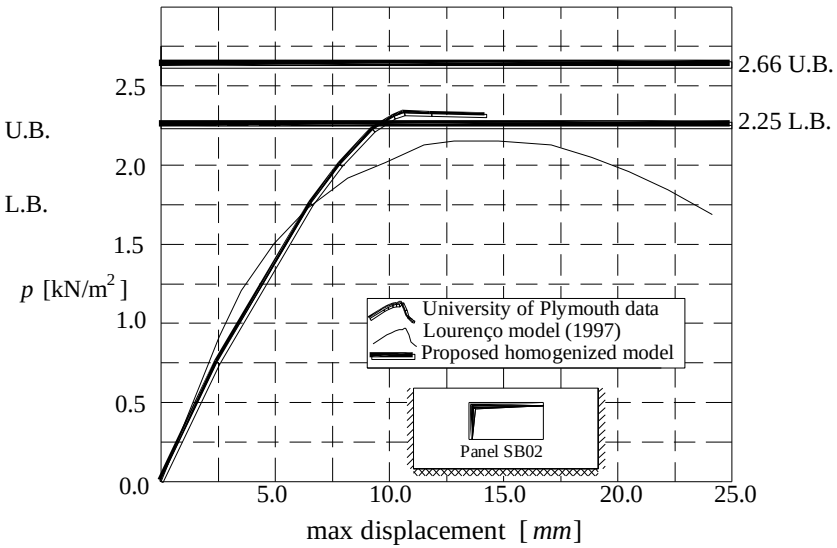
EXTENSION TO SLABS



Lower Bound

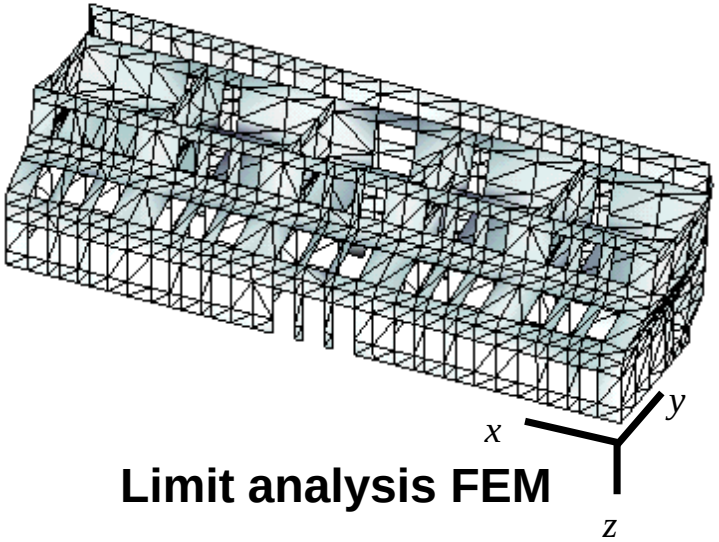


Upper Bound

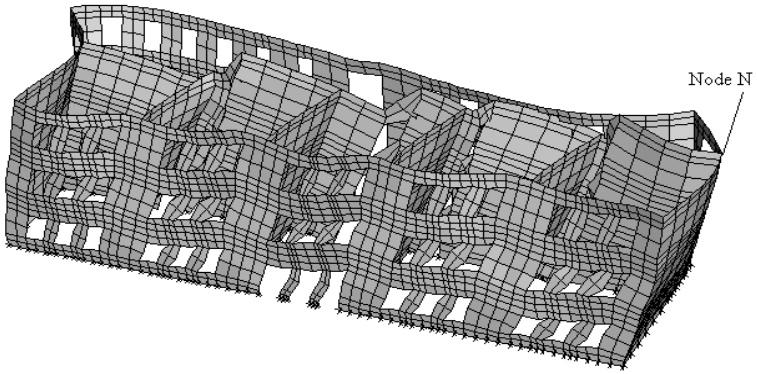


Results

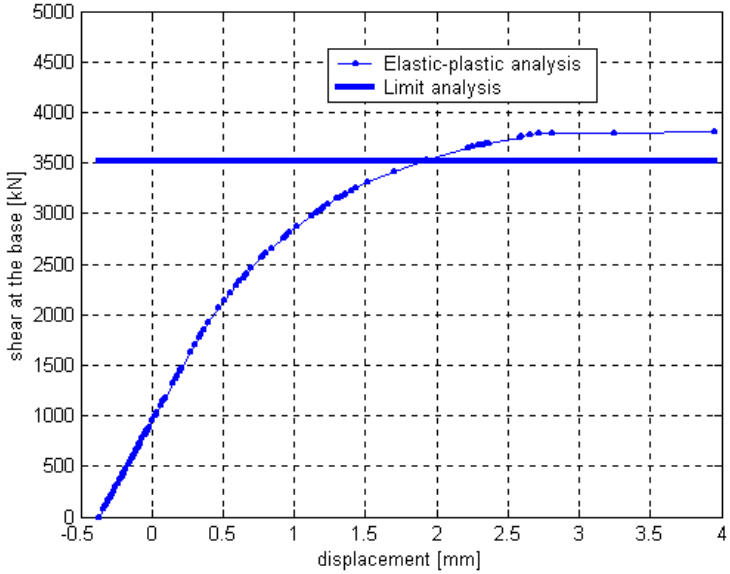
APPLICATION TO A SCHOOL BUILDING IN ITALY



Limit analysis FEM

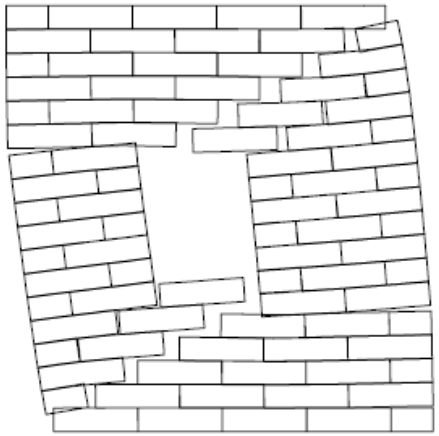


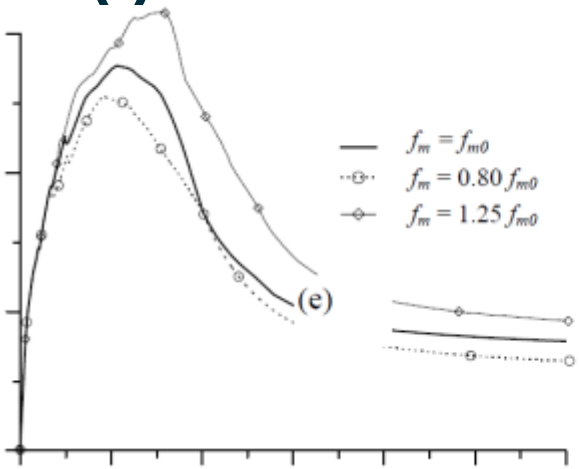
FEM standard model

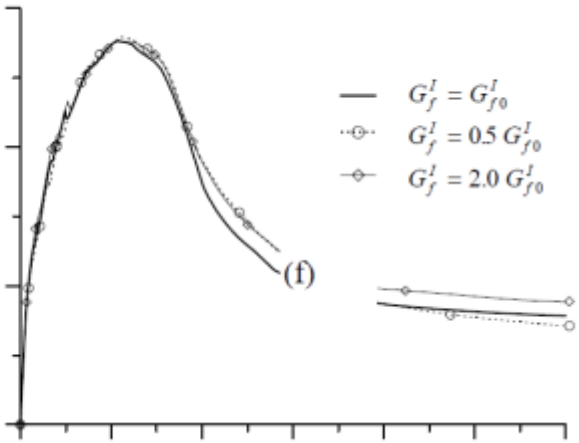


Results

Sensitivity Analysis (I)



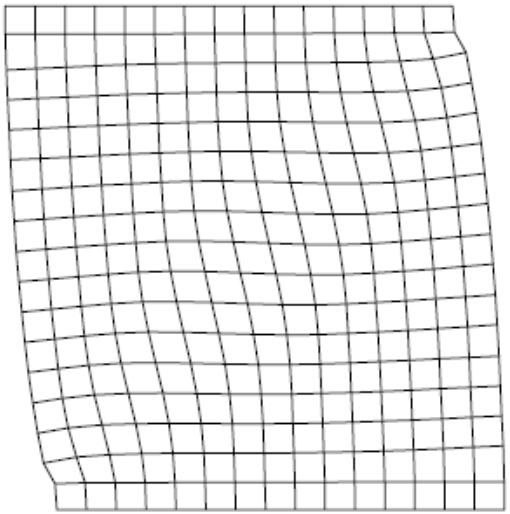


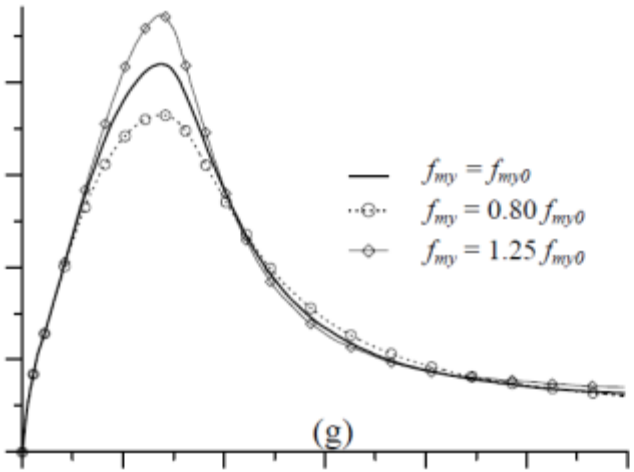


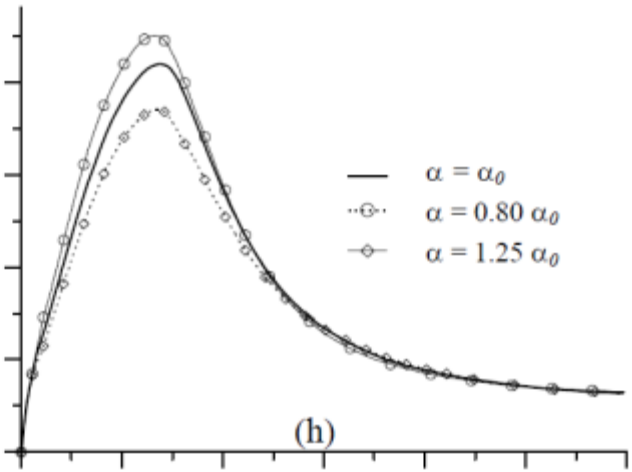
Parameter	k	f_t	c	$\tan\phi$	f_m
Divided by 1.25	52.84	55.92	55.70	50.50	50.79
Multiplied by 1.25	58.80	55.47	55.08	60.46	63.17
Difference to original	6.2%	1.1%	0.6%	9.6%	14.1%

Parameter	G_f^I	G_f^{II}	G_f^c
Divided by 2.0	55.88	56.16	46.68
Multiplied by 2.0	55.19	55.54	65.54
Difference to original	0.9%	1.4%	18.6%

Sensitivity Analysis (II)





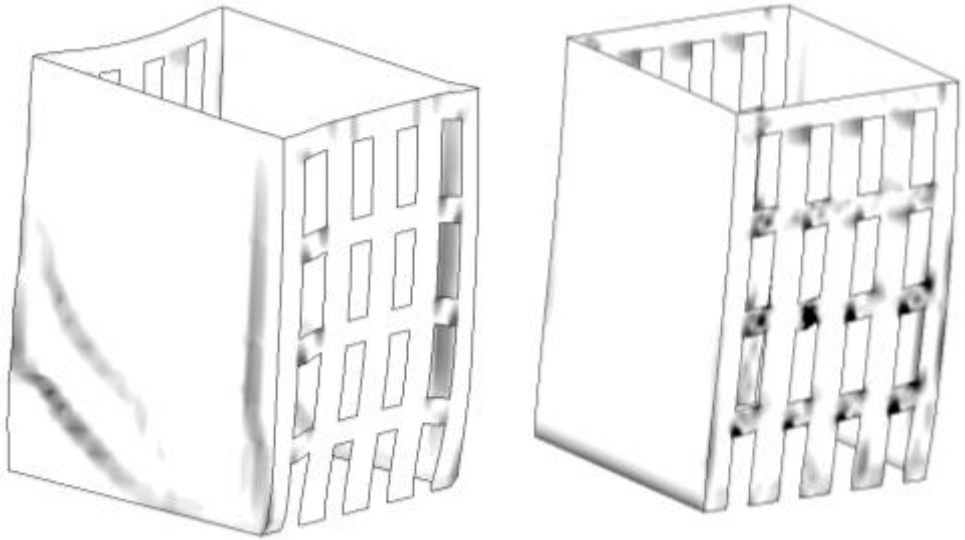


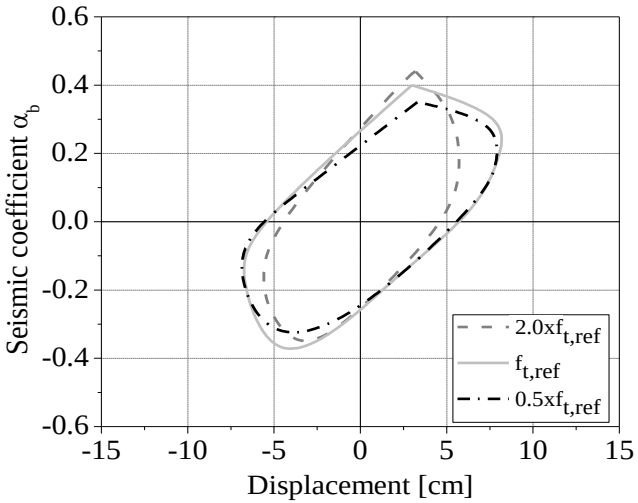
Parameter	E	f_{tx}	f_{ty}	f_{mx}	f_{my}	α	β
Divided by 1.25	162.4	167.8	168.0	162.8	146.0	180.5	164.6
Multiplied by 1.25	172.9	168.3	168.0	172.7	189.4	148.5	172.7
Difference to original	3.4%	0.2%	0.1%	3.2%	13.1%	11.7%	2.7%

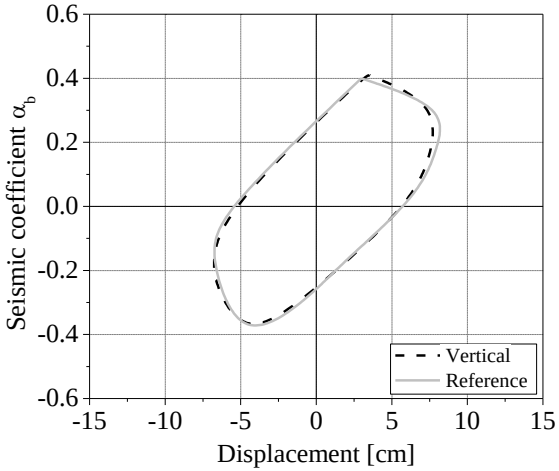
Parameter	γ	G_{fx}	G_{fy}	G_{fcx}	G_{fcy}
Divided by 2.0	180.3	167.5	167.8	162.5	151.1
Multiplied by 2.0	151.8	169.3	168.4	169.5	179.0
Difference to original	9.7%	0.7%	0.2%	3.3%	10.1%

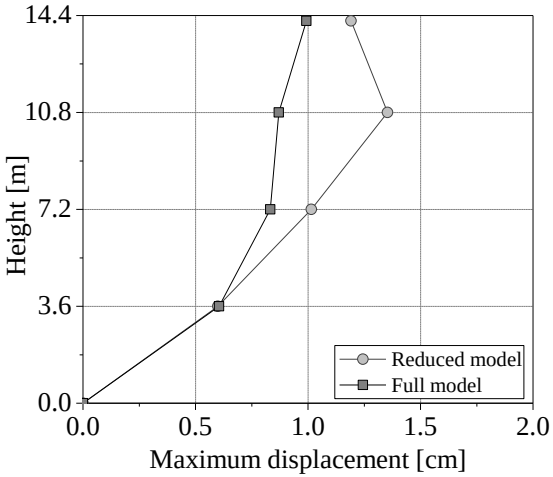
(k) (l)

Sensitivity Analysis (III)









1. Moderate influence of material data
2. Low influence of vertical earthquake action
3. Reduced scale models (with Cauchy law of similitude) is conservative

DIFFERENT MODELS = DIFFERENT RESULTS ???

Static Analysis Methods (I)

- **Linear Elastic Analysis**

  elastic properties + maximum admissible stress

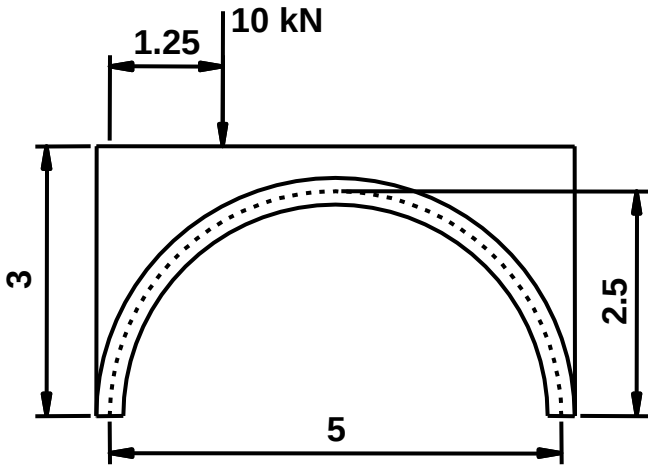
- **Kinematic Collapse Mechanism Analysis**

  inelastic properties = friction angle + tensile and compressive strengths

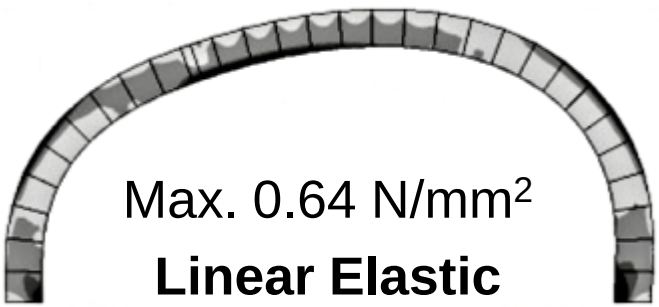
- **Static Thrust Line Analysis**

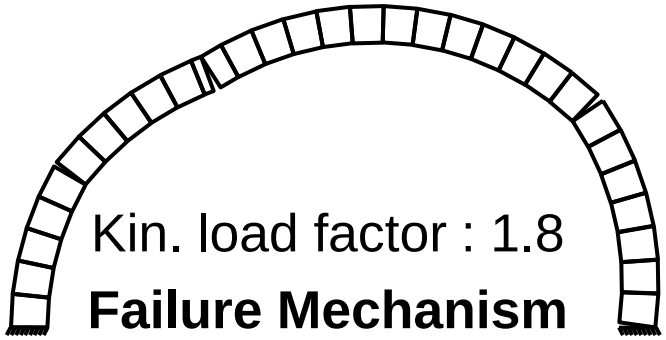
- **Non-linear Analysis (Physical and Combined)**

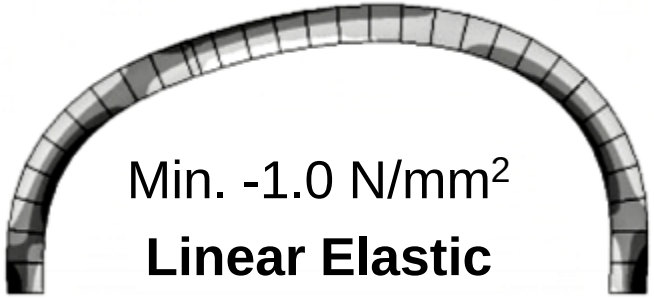
  FULL inelastic properties (ft = 0 and ft ≈ 0) + elastic properties

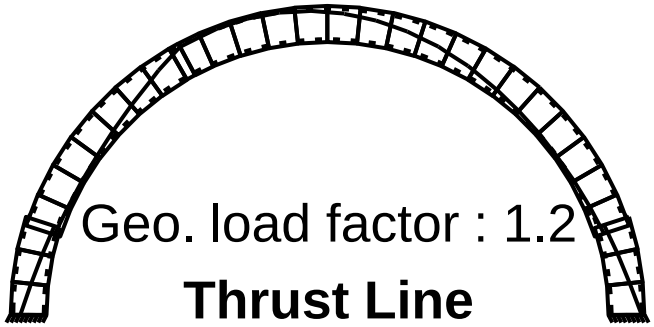


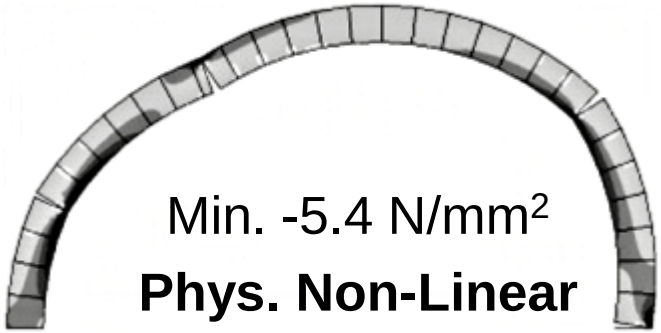
Static Analysis Methods (II)

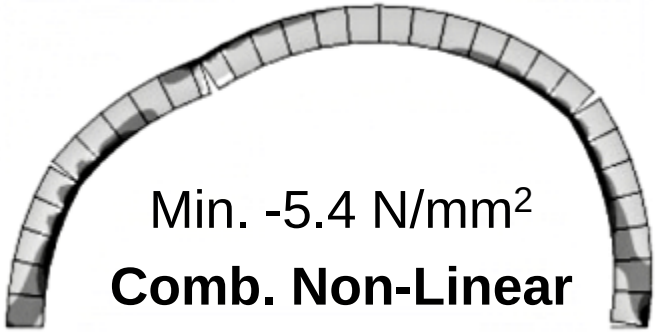




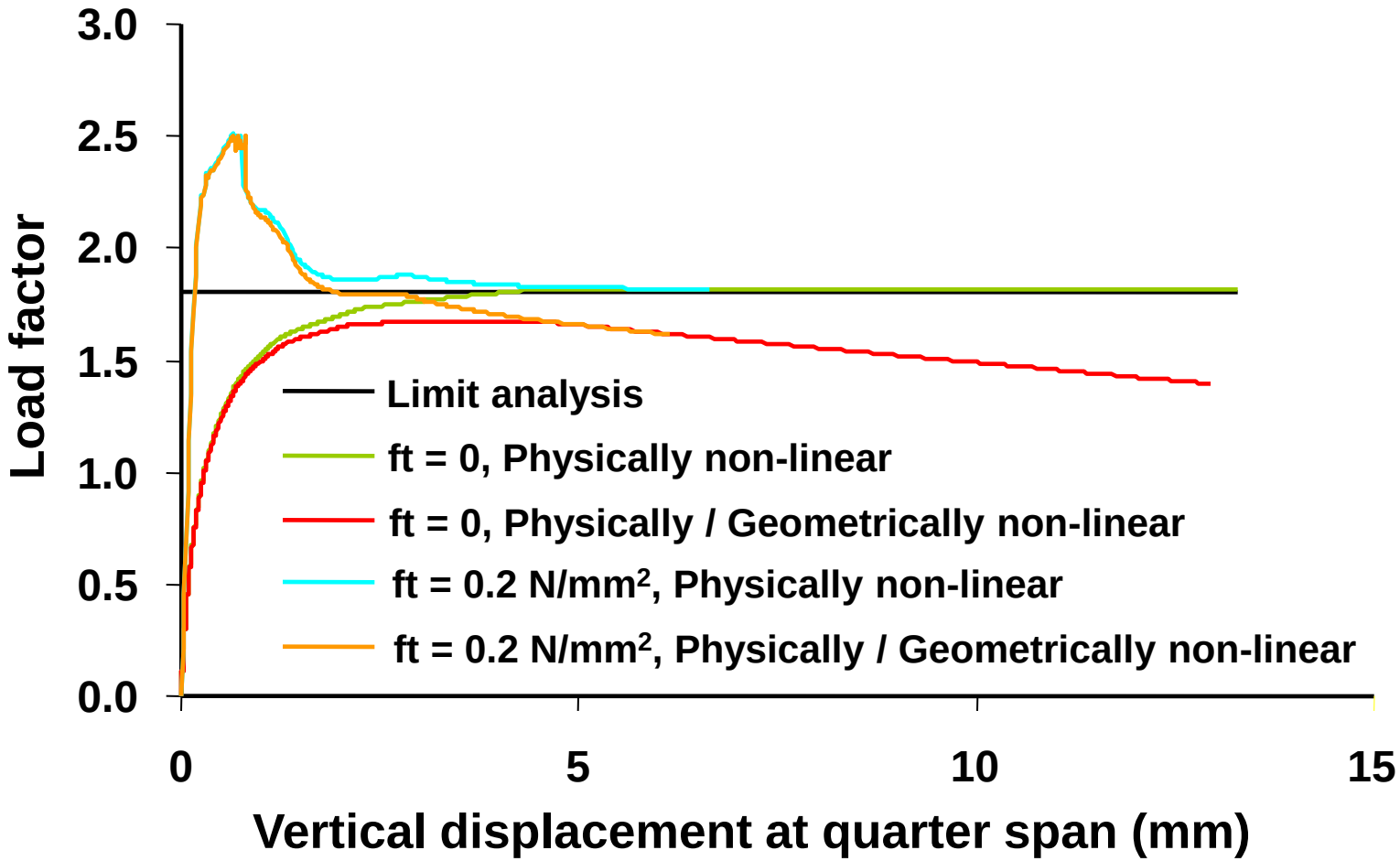




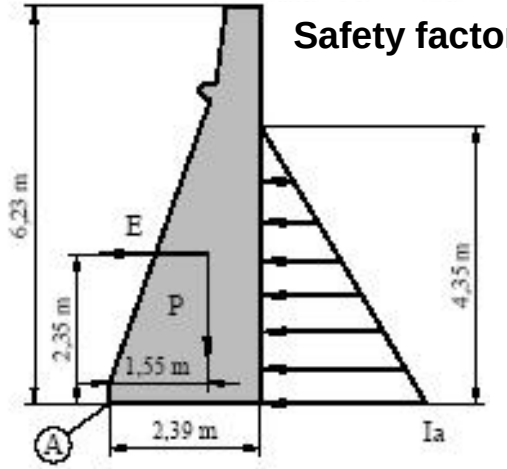


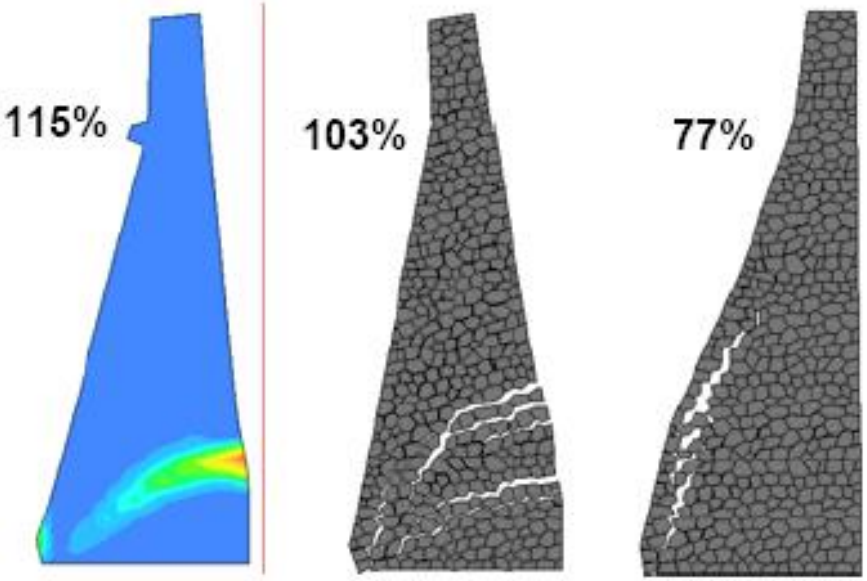


Static Analysis Methods (III)

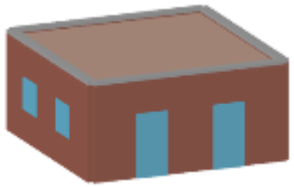


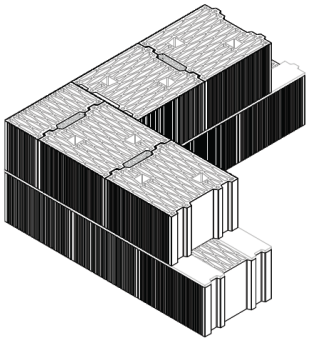
More on Static Analysis Methods…

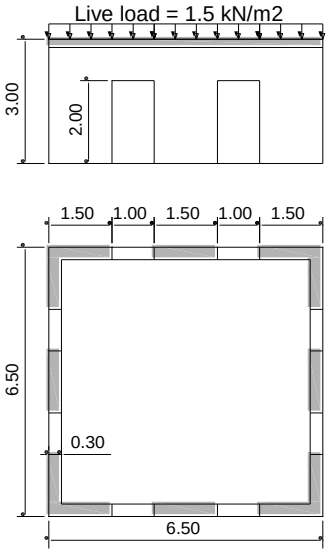


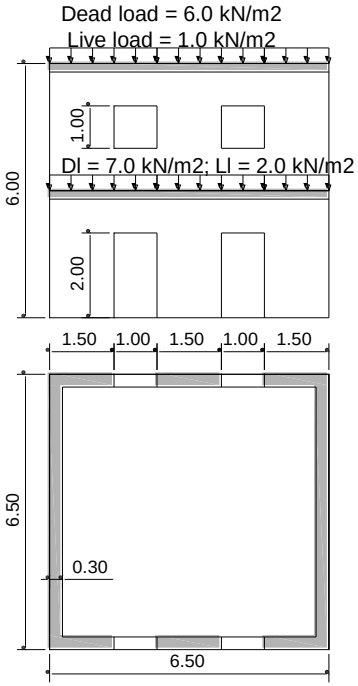


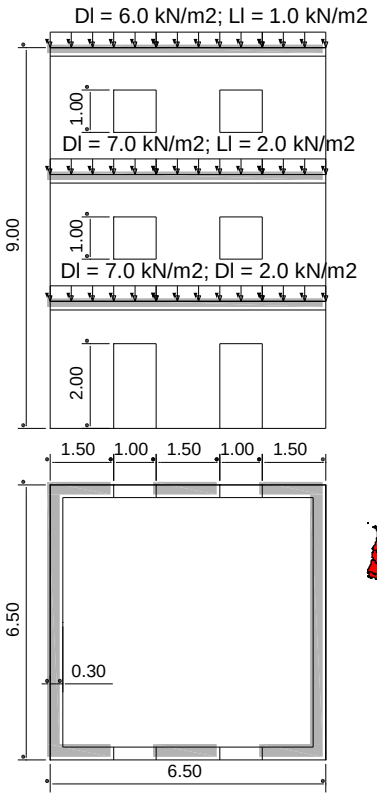
Using the Right Analysis Method!





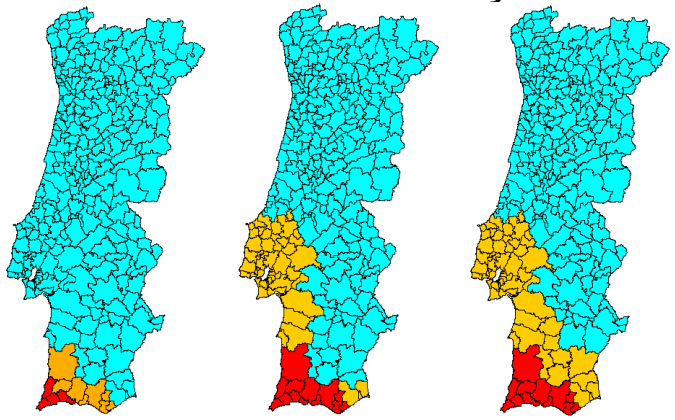




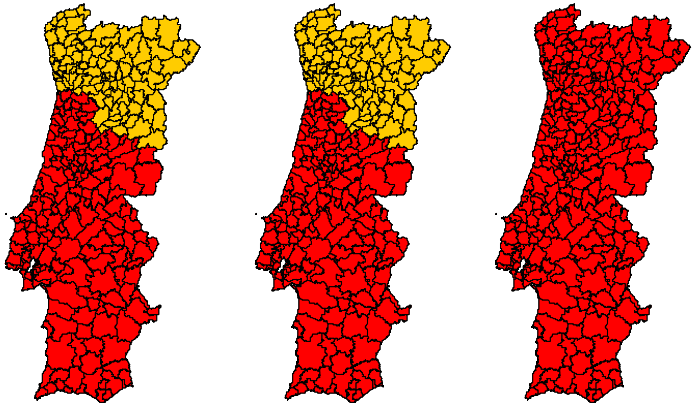


1 storey **2 storeys** **3 storeys**

Nonlinear Analysis



Elastic Analysis (q=1.5)



Cannot be used
Can be used for hard soils
Can be used for good soils

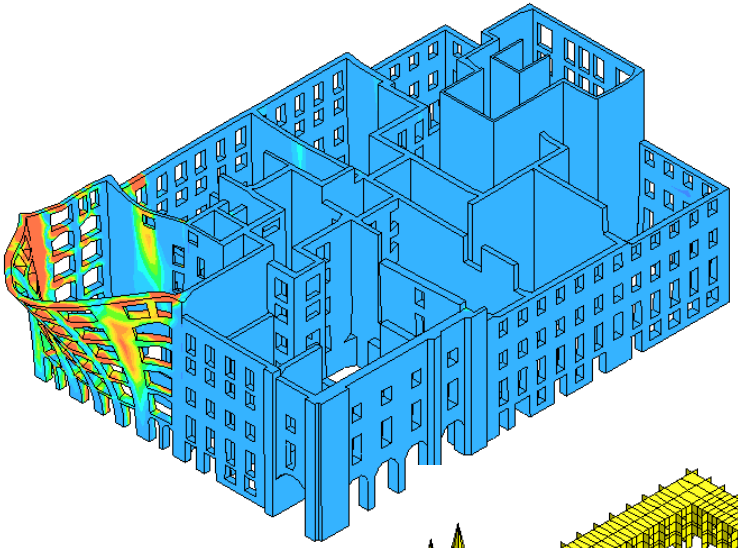
UNIVERSITY OF MINHO
Civil Engineering Department
Paulo Lourenço

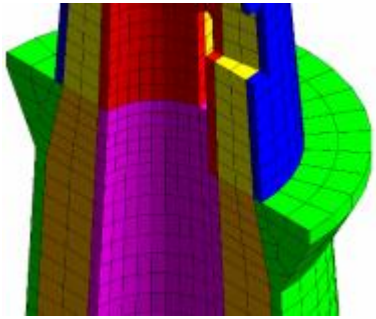
KEEP IT SIMPLE!

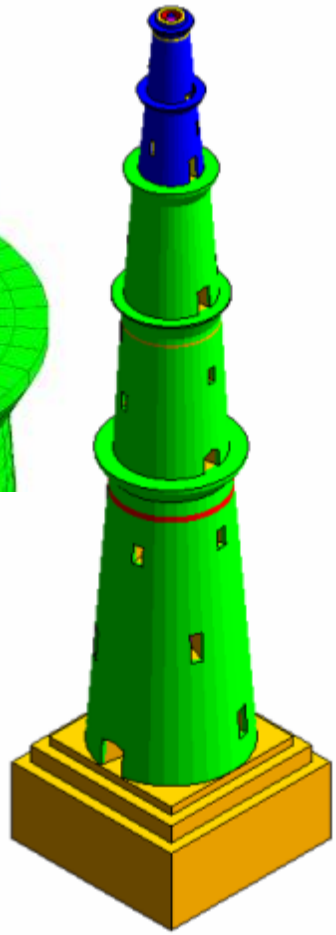
Modeling of Historical Structures (I)

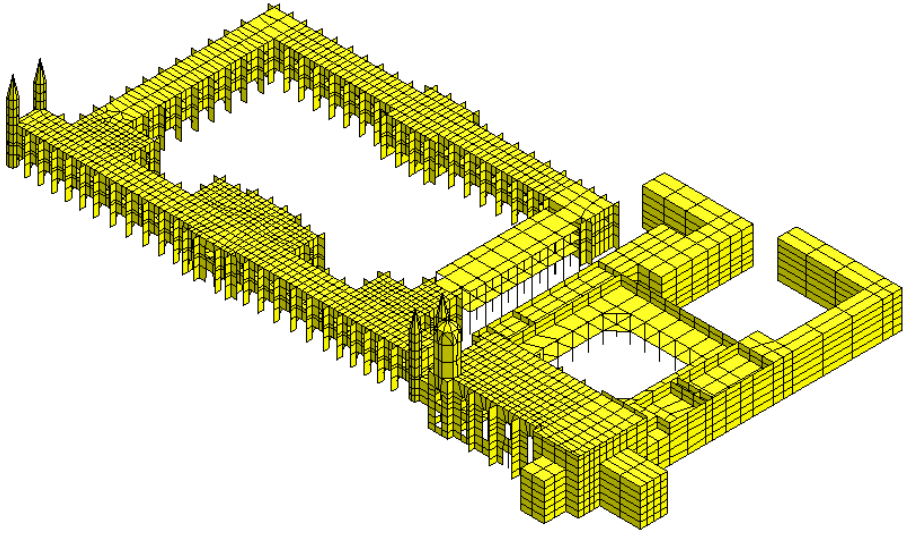
- In contrast to modern structures, it is not straightforward to define the conditions under which a given idealization of the geometry is applicable
- Usually, the geometry of historic masonry structures is rather complex as there is no distinction between decorative and structural elements. Therefore, as a first impression, it would seem reasonable to advise the use of three-dimensional elements. But this impression is erroneous!
- The practical analysis of historic masonry structures entails severe simplifications. As a rule, the geometric idealization should be kept as simple as possible, as long as it can be considered adequate for the problem being analyzed. In particular:
  - Fully three-dimensional models are usually very time-consuming with respect to preparation of the model, to perform the actual calculations and to analyze the results. Several authors use eight-node bricks, with one element over the thickness of the walls or vaults. The errors associated with such a discretization are very large, even for linear elastic analysis, yielding meaningless results;
  - The results of models incorporating shell elements are fairly difficult to analyze owing to the variation of stresses along the thickness of the elements. In addition, the large thickness of the structural elements may yield a poor approximation of the actual state of stress;
  - Increasing the detail and size of the model might result in a large amount of information that blurs the important aspects

Nice pictures (several man-months of work)…



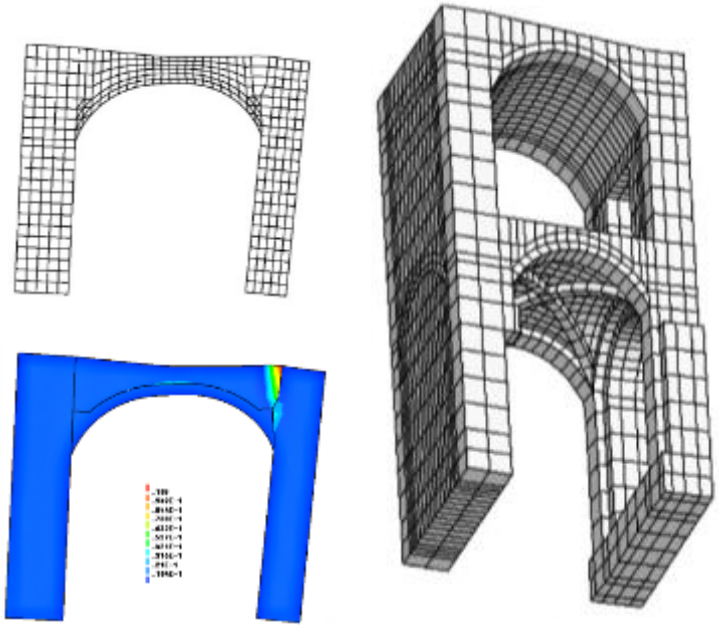




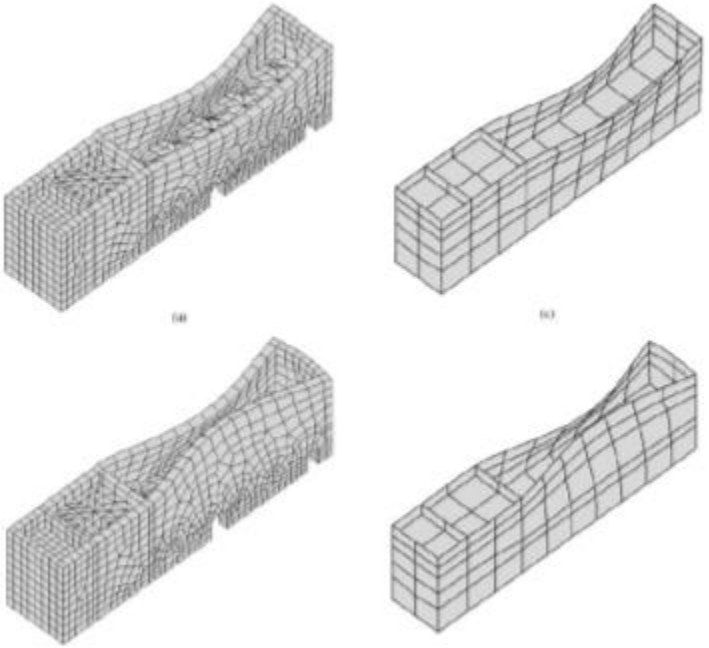


Modeling of Historical Structures

- If possible, it seems preferable: (a) to use two-dimensional models rather than three-dimensional models; (b) to avoid using shell elements in areas important for the global behavior of the structure; and (c) to model structural parts and details instead of modeling complete and large structures



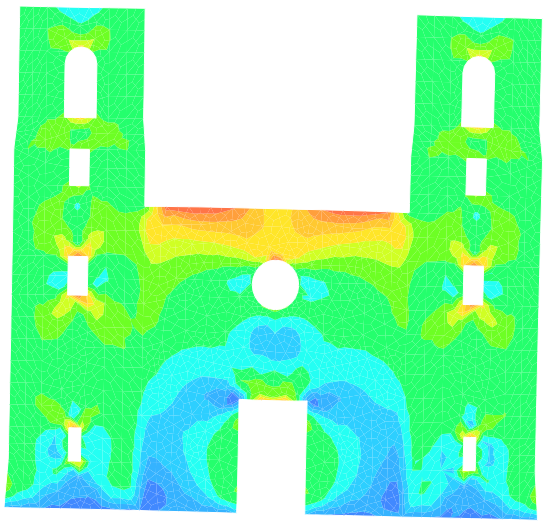
Cloister in Monastery of Salzedas. Using a 2D model instead of a 3D model (already it self a simplification: only one bay). For linear elastic analysis the difference was lower than 10%

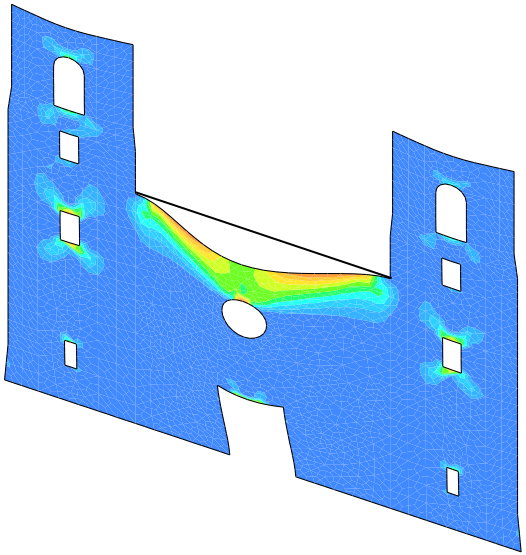


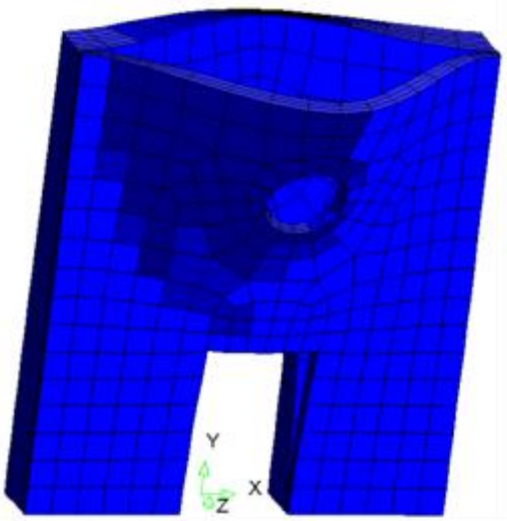
Refectory of the Monastery of Jerónimos. In a modal analysis, the 3D model yields similar results to the model for the vibration modes. Wall thickness was corrected, due to the additional stiffness provided by the intersection of the thick walls

Modeling of Historical Structures

- Details…

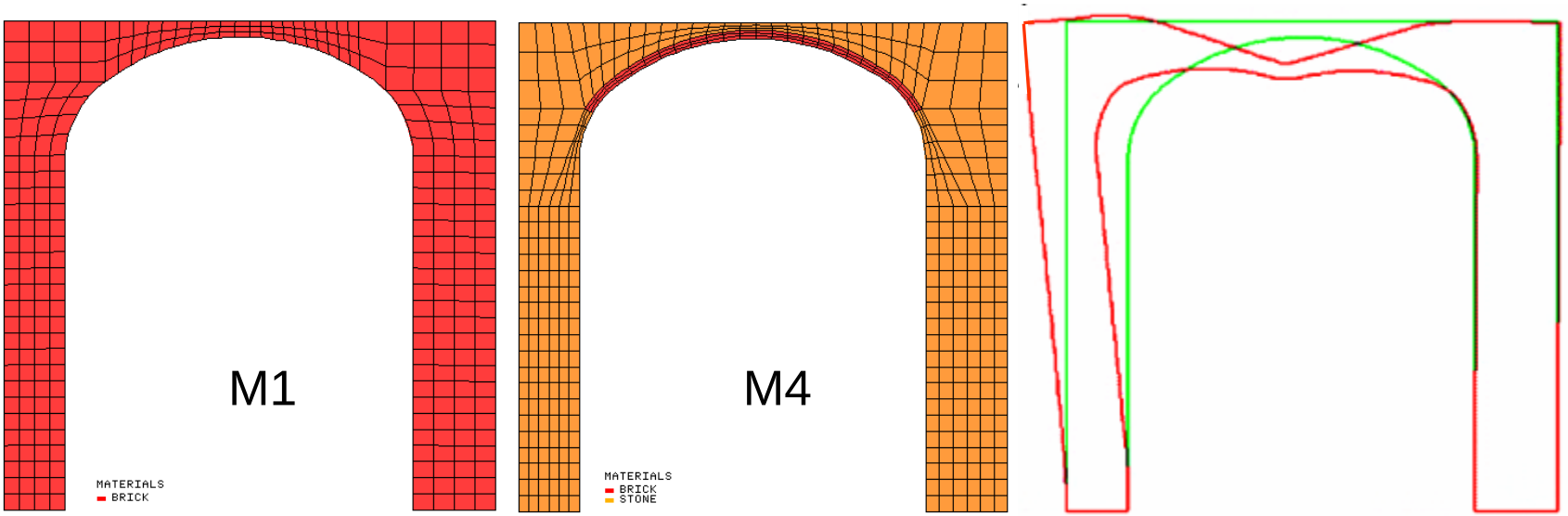




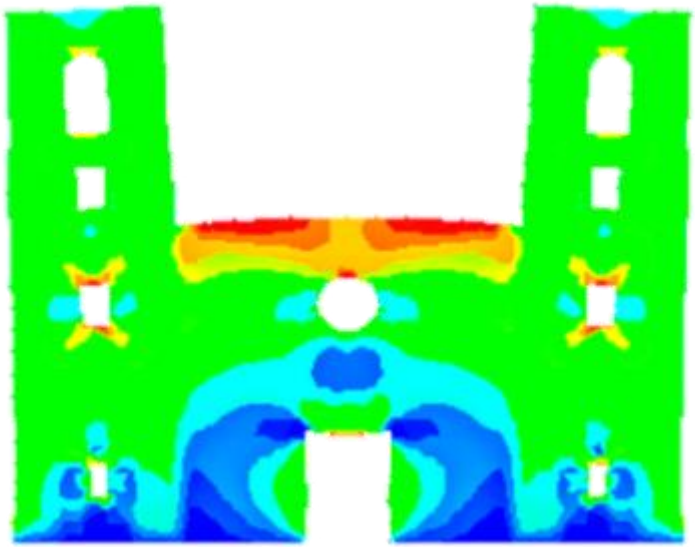


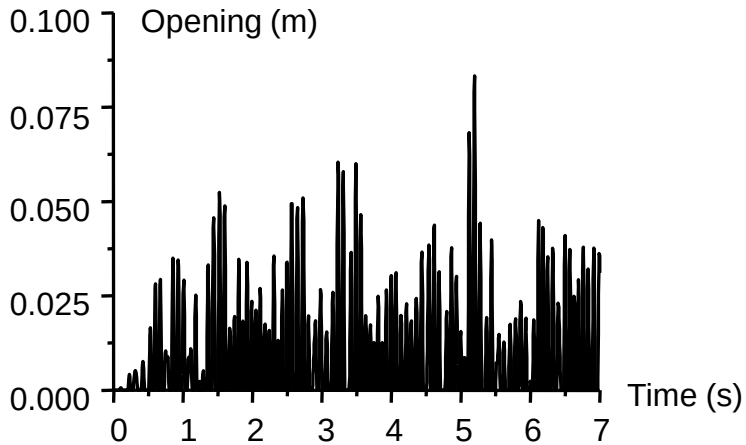
Cloister in Outeiro. Three-different simple models to understand the damage: 2D, Shell and 3D

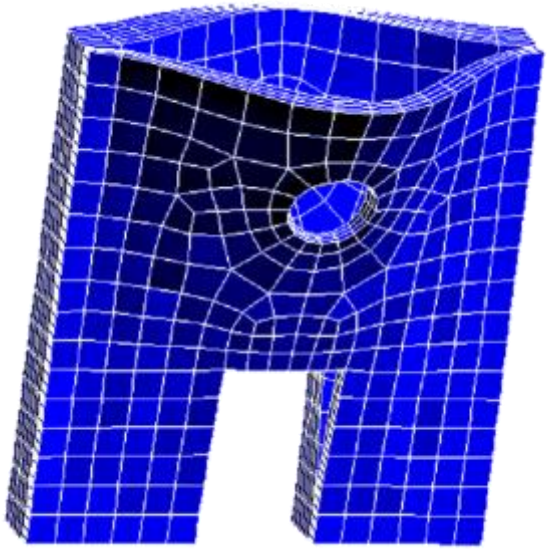
Lethes Theatre, Faro



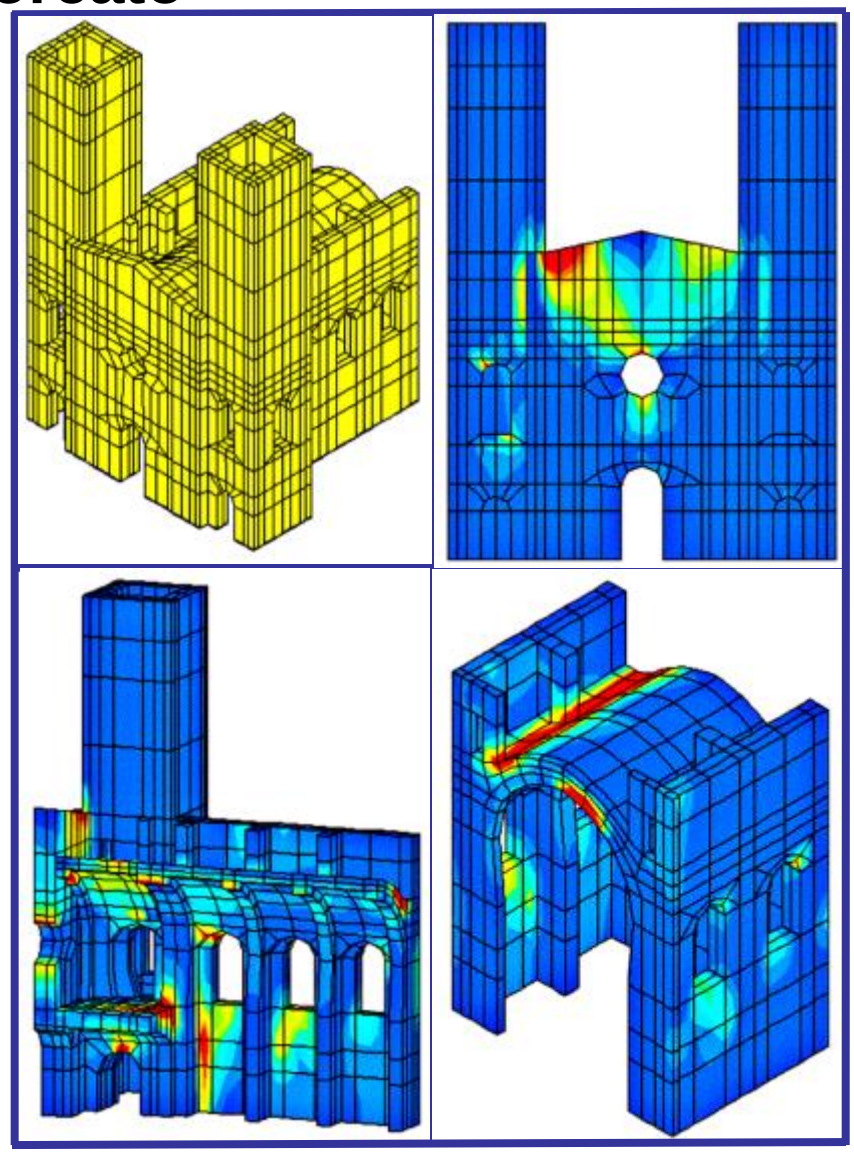
Holy Christ Church, Outeiro



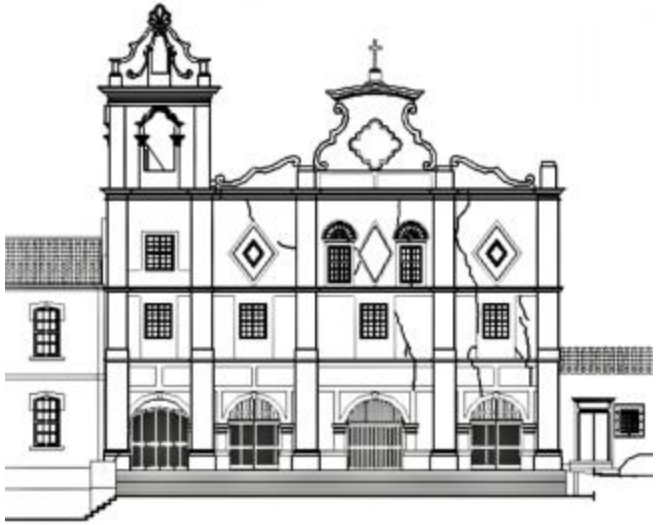


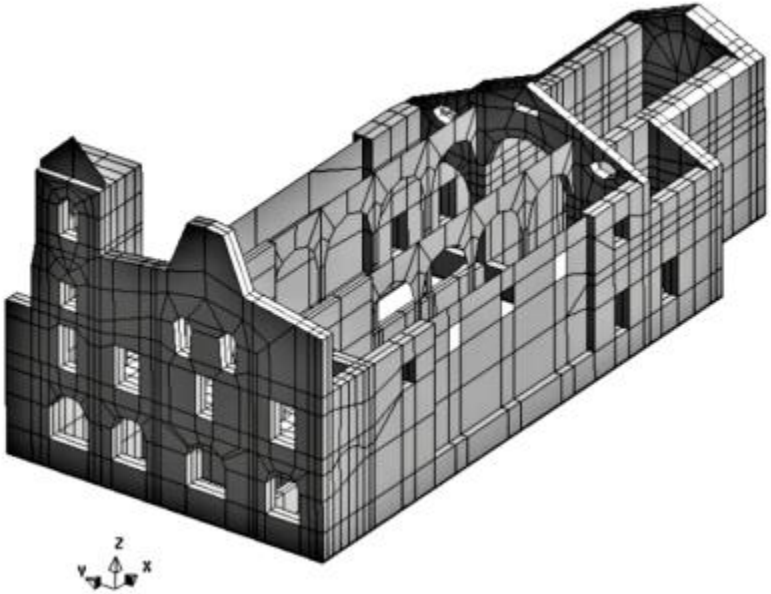


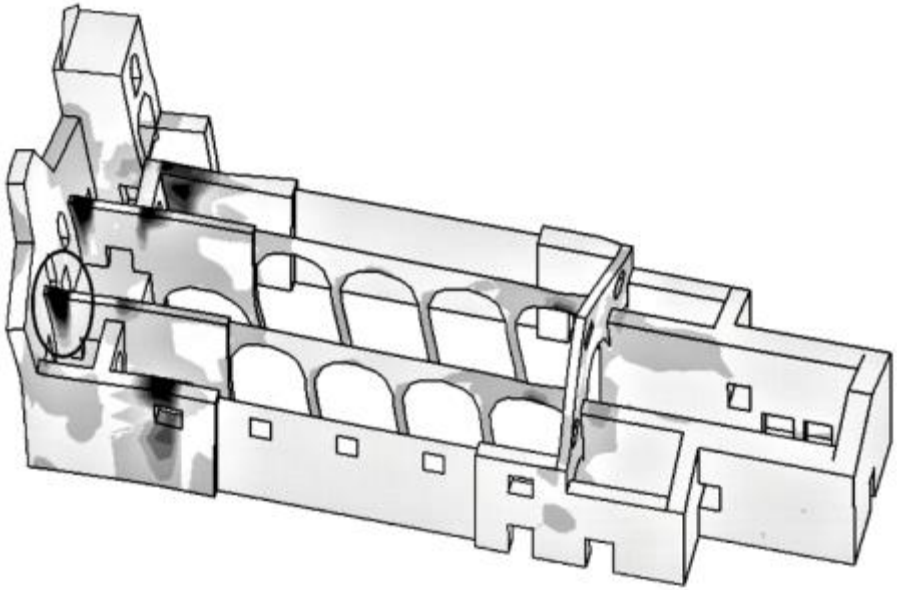
São Torcato Sanctuary, São Torcato



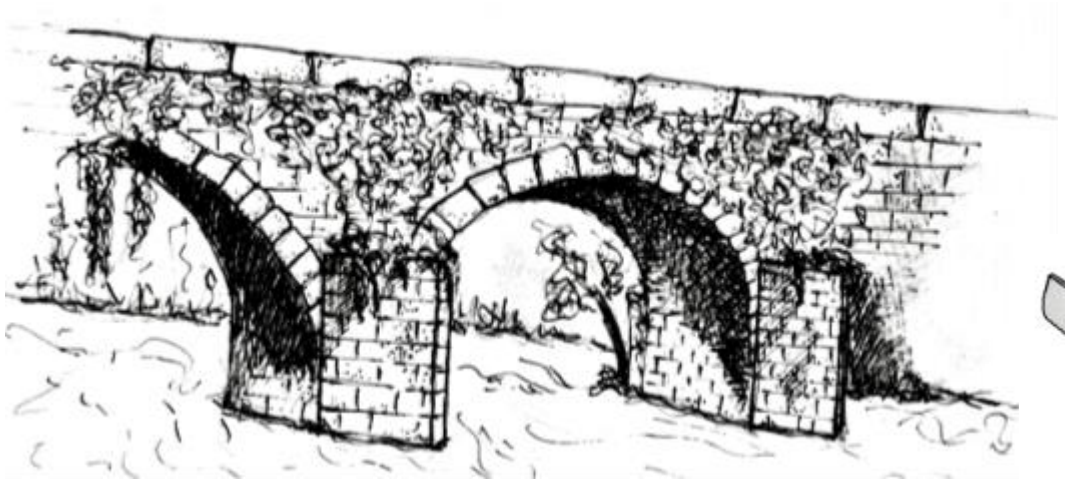
Saint Francis Church, Horta, Azores

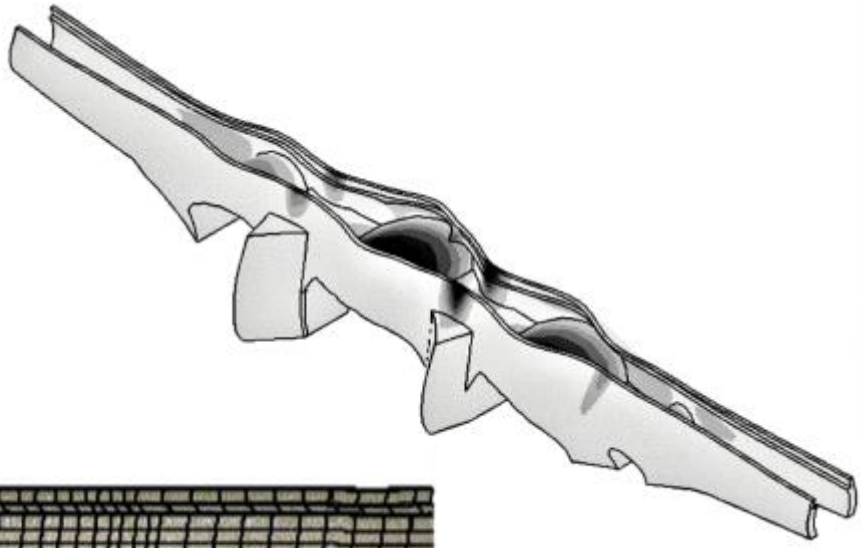


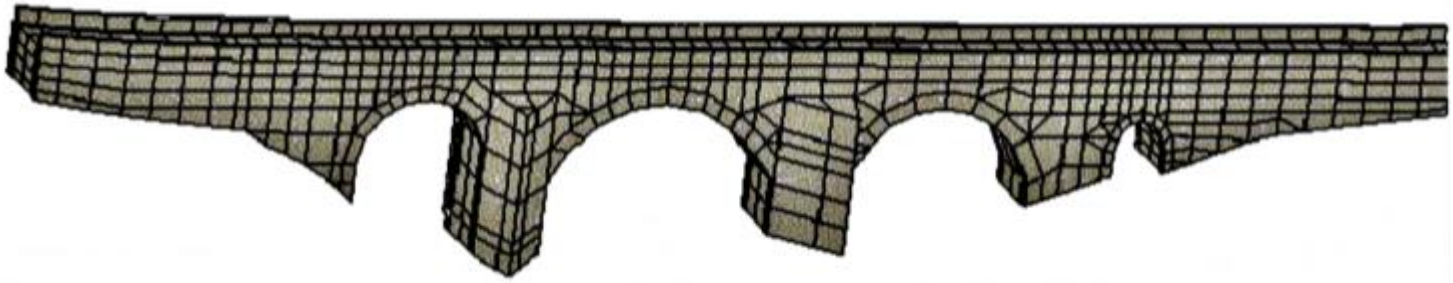




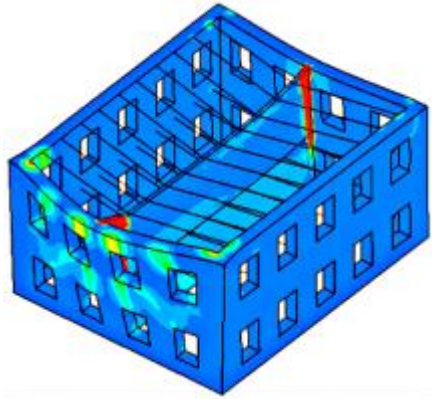
Donim Bridge, Donim

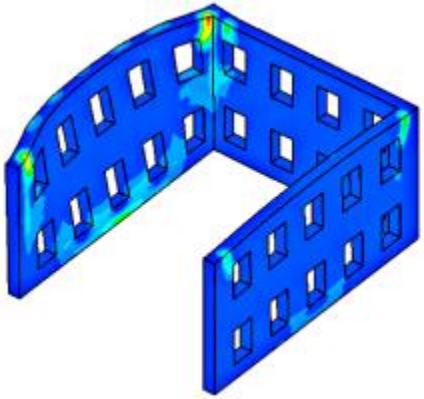


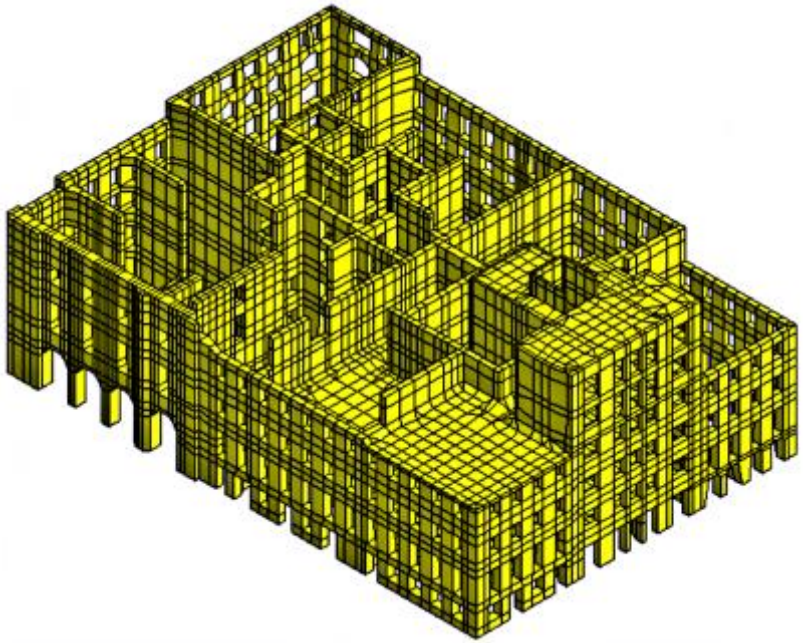


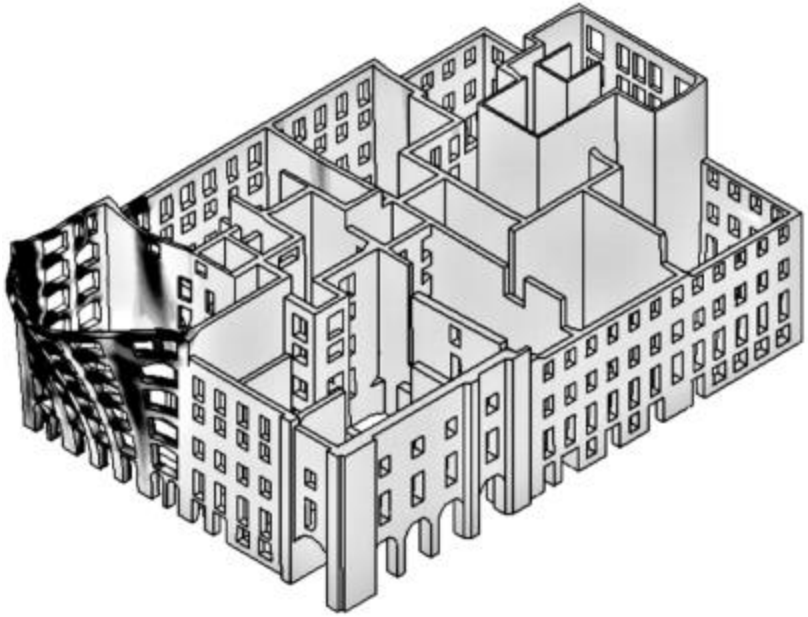


Typical downtown construction of Lisbon









CONCLUSIONS

CONCLUSIONS

- Structural analysis (quantitative output) is not the only information considered for decision of safety, even if it is very relevant. Subjectivity and uncertainty are there. Use also other sources of knowledge
- Advanced tools for masonry structural analysis are available. Information on material data to feed advanced models is available
- Difficult task, which requires training and specific skills: (a) scatter of properties, lack of original design elements / Non-conforming execution, deficient structural connections, load transfer, …; (b) different materials, technologies, …; (c) lack of education and non-applicable codes
- Different approaches can provide different results. Be sure to validate the models and use a correct approach
- Keep it simple, if you can ☺!

Structural Modeling of Historical Constructions

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