Analysis Methods for Unreinforced Heritage Masonry (I): Masonry Behavior and Modeling

isise

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Introduction

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The seismic problem (I)

- Earthquakes hardly cause deaths, being the collapse of buildings the major cause of deaths and loss
- The scenarios for a large earthquake in Portugal (similar to 1755) predict about 10.000 deaths and a loss of 100 to 200% of the GDP

Artistic image of 1755 Lisbon earthquake

Carmo church, Lisbon

A perfect disaster: tsunami with 10 m, fire for 5 days, 85% of the buildings destroyed, up to 90.000 deaths = 30% of population, Enlightenment – Kant / Voltaire)

Acceptable

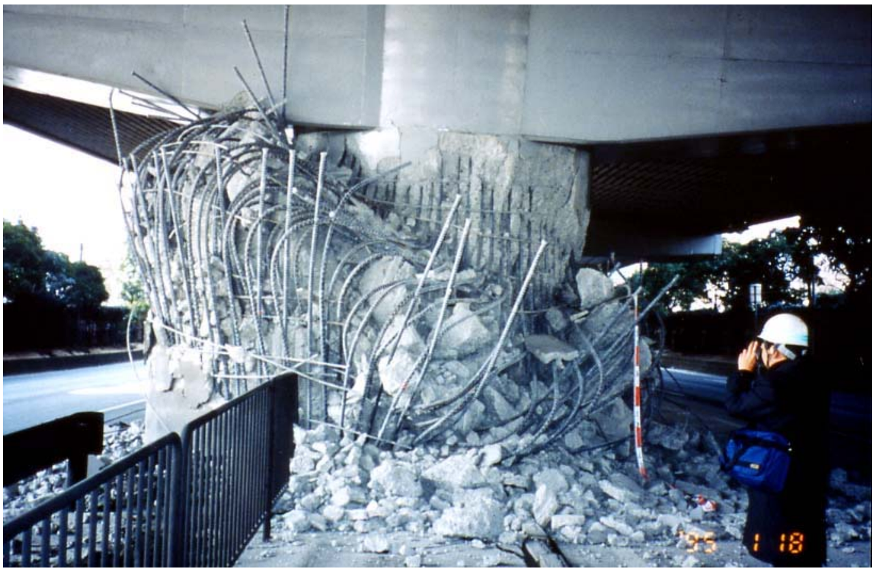
KOBE Earthquake, 1995

Earthquake magnitude was higher than 50% the design value:

Extreme event

The damage in the column is acceptable (even if not desired)

Unacceptable



Damage in this column is unacceptable

Acceptable

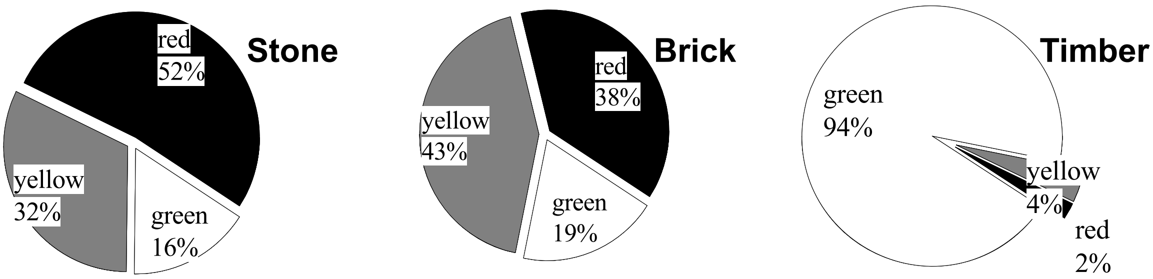
- Worst case scenario in masonry: embedded ring beam + unfilled vertical joints
- Light damage up to the design earthquake in Lisbon (rock)
- Ductile damage for 2.5x the design earthquake in Lisbon (rock)

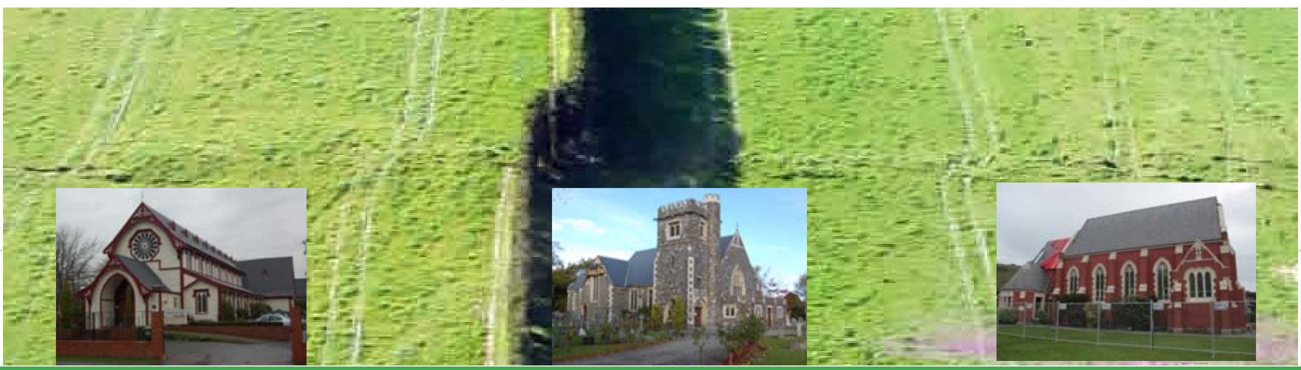
Unacceptable

- Existing masonry buildings are usually rather vulnerable: (a) fragile materials; (b) heavy construction; (c) inadequate connections.
- Simple and moderate cost measures can make drastically change the situation

Churches in New Zealand (Earthquakes 2010-11), M7.1

- Red: unsafe building with access forbidden
- Yellow: safety compromised but urgent access allowed
- Green: no restrictions





Preservation Engineering

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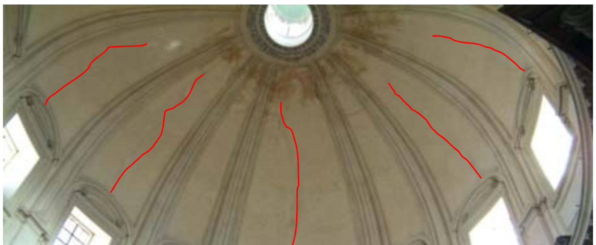
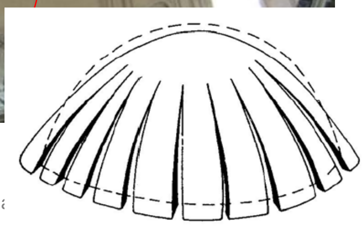
Preservation of heritage structures

- Not only appearance and materials of historic structures are to be preserved; also their resisting mechanisms are to be investigated, understood and preserved
- Difficult task, which requires a different approach and skills from those employed in designing new construction:
  - Complexity (scatter of properties, lack of original design elements / Non-conforming execution, deficient structural connections, load transfer…)
  - Different knowledge (materials, technologies, …)
  - Lack of education and non-applicable codes
  - Advanced numerical and experimental tools have justification

What not to do (I)?



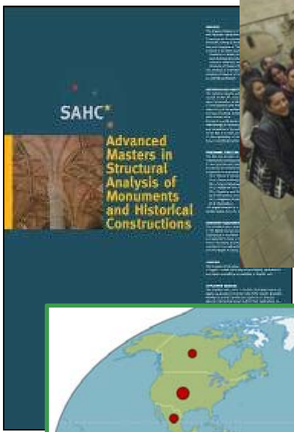


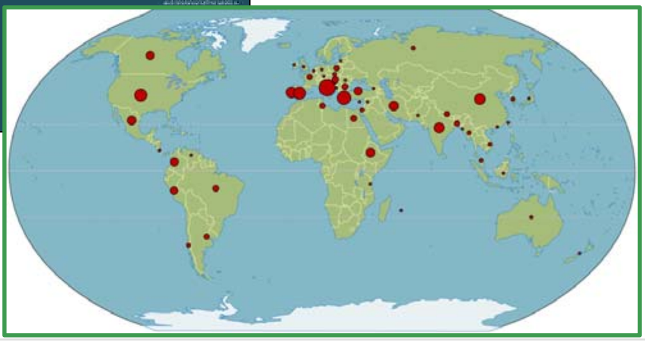
The need to understand materials, structural arrangements and construction techniques from existing buildings

What not to do (II)?

It is necessary to adopt adequate safety evaluation procedures (history, quantitative analysis, qualitative analysis, experimental analysis)

MSc in Structural Analysis of Monuments and Historical Constructions





- ❑ 300 students so far
- ❑ 60 countries
- ❑ About 400 applications/year
- ❑ About 40 students/year (20+20)

- ❑ Practice & Research

- ❑ Overall rating program 88%
- ❑ Quality teaching staff 78%
- ❑ 2 Robert Silman Fellows for alumni
- ❑ 3 GCI internships for alumni
- ❑ Several awards for MSc theses and papers
- ❑ Selection for PhD programs worldwide (ETH, UCSD, …)

Edition #10 in 2016/2017

Deadline January 15

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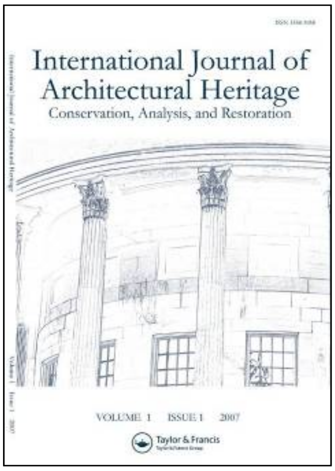
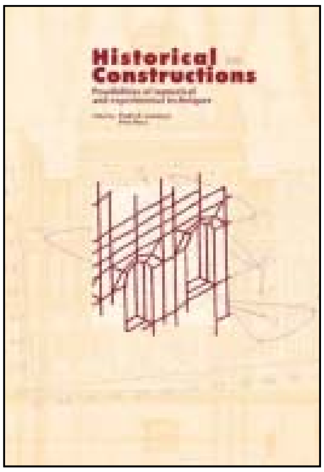
www.msc-sahc.org

And more…



Taylor and Francis,
Since 2007



Guimarães, 2001
500 participants

- ❑ Conference series: Structural Analysis of Historical Constructions

- ❑ 250 – 500 participants

- ❑ 1995-8 Barcelona, Spain
- ❑ 2001 Guimarães, Portugal
- ❑ 2004, Padua, Italy
- ❑ 2006, New Delhi, India
- ❑ 2008, Bath. UK
- ❑ 2010, Shanghai, R.P. China
- ❑ 2012, Wroclaw, Poland
- ❑ 2014, Mexico-City, Mexico
- ❑ 2016, Leuven, Belgium

Basis of Structural Analysis

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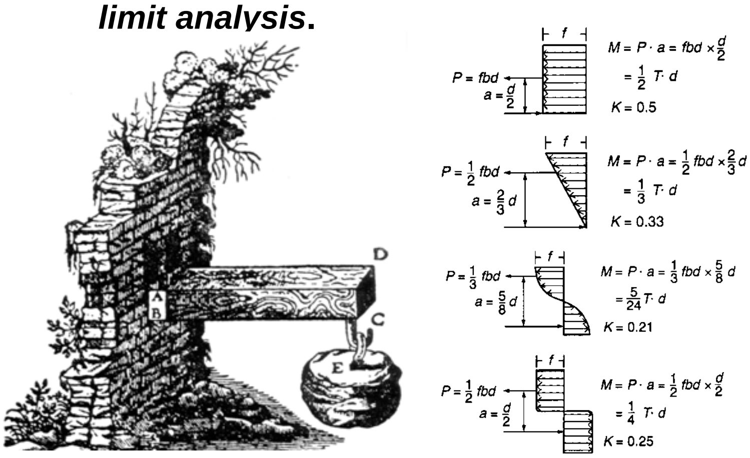
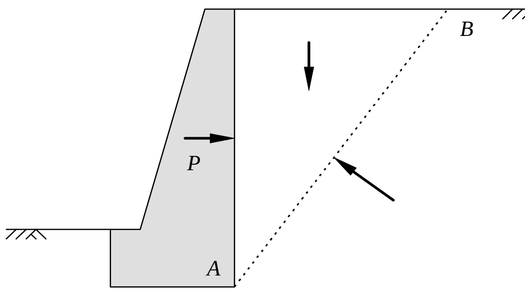
Introduction (I)

- “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)

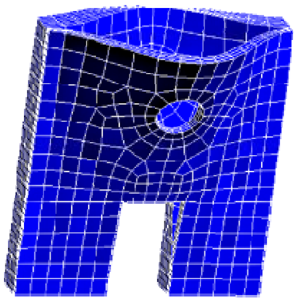
Introduction (II)

- As structural collapse does not generally coincide with the appearance of the first crack or localized early crushing, it seems that the elasticity theory is a step back with respect to limit analysis
- Full nonlinear analysis (representing the most advanced form of structural analysis) covers the complete loading process, from the initial “stress-free” state, through the weakly nonlinear behavior under service loading, up to the strongly nonlinear behavior leading to collapse
- Interest has been growing since 1970’s but it remains a field for selected (few) specialists due to complexity (knowledge) and costs (time) involved
- The possibilities are immense and several commercial software packages include some form of nonlinear behavior, but an incorrect use can be very dangerous

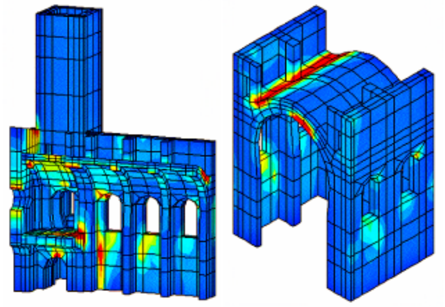
Introduction (III)

- The modern use of nonlinear analysis focuses mostly on these three fields:
    - Complex / stringent safety requirement structures (e.g. nuclear plants, dams, bridges)
    - Virtual laboratory for parametric studies
    - Existing structures (evaluation, repair, rehabilitation)
- One difficulty is to define which phenomena need to be included in the analysis (static or dynamic response; short term or long term loading; imperfections; residual stresses; etc.)
- KISS = Keep it simple, structurally

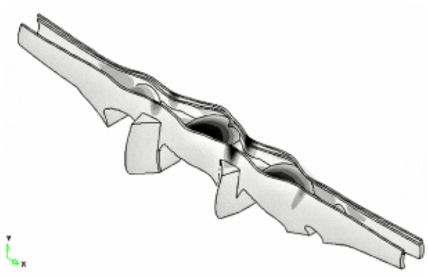
Solving Engineering Problems & Definition of Practical Rules



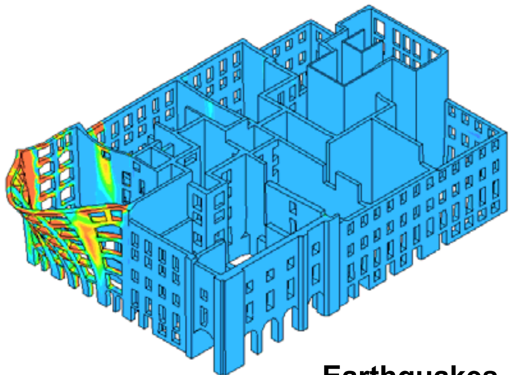
Pounding



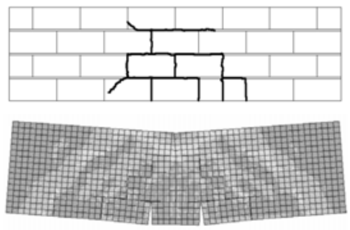
Settlements

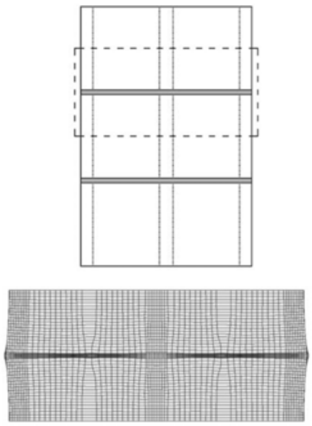


Vehicles



Earthquakes



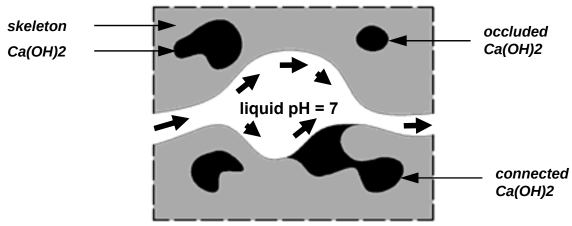


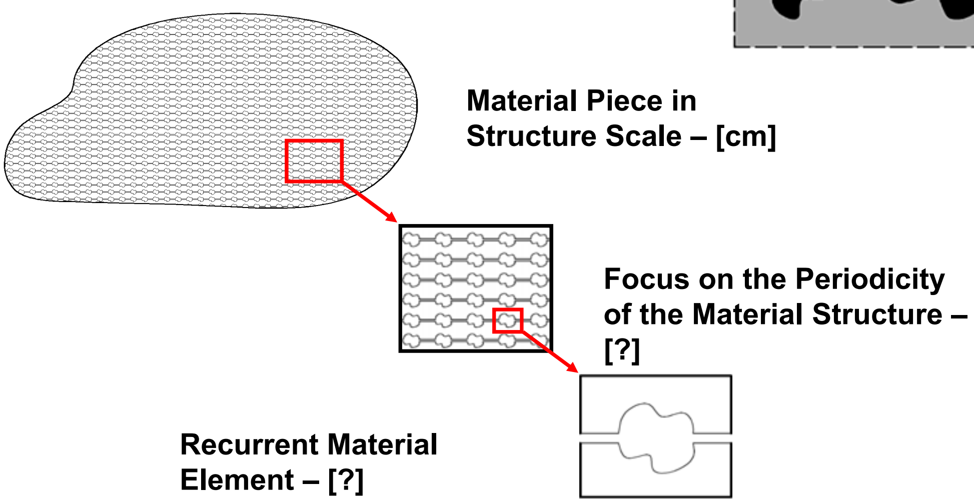
Parametric studies

Step 1: Understand Masonry

Materials with internal structure

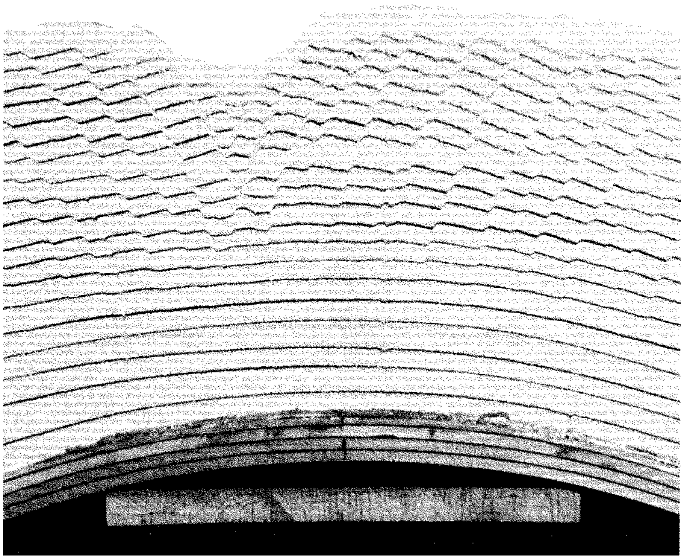
Materials with micro-structure (Multi-scale modeling)



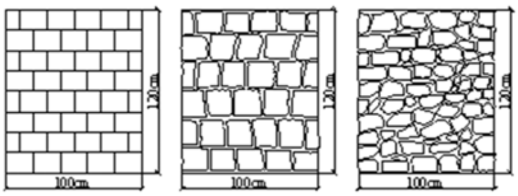


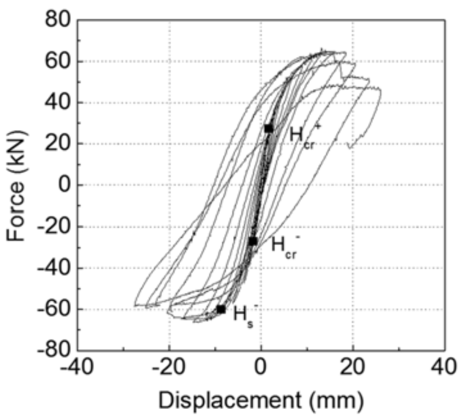
Materials with micro-structure

- Localization of Deformation



Why is this relevant for mechanics?

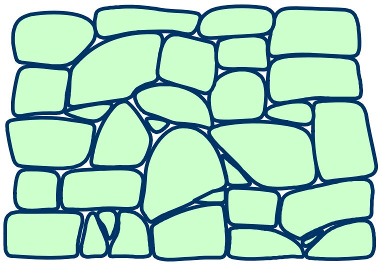




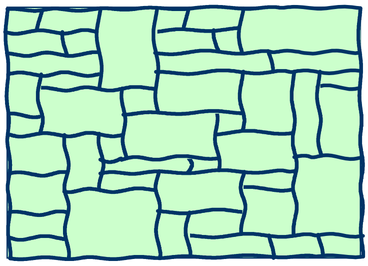
Stone walls

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

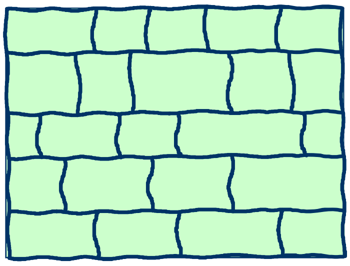
Variability of Existing Masonry



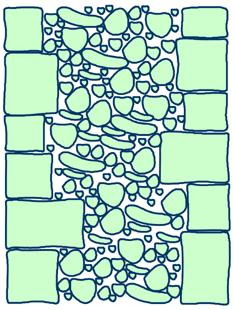
Rubble masonry



Ashlar masonry



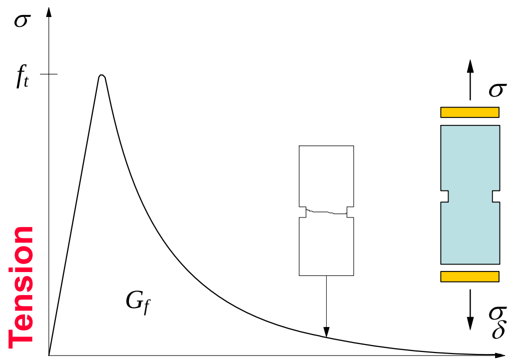
Coursed ashlar masonry

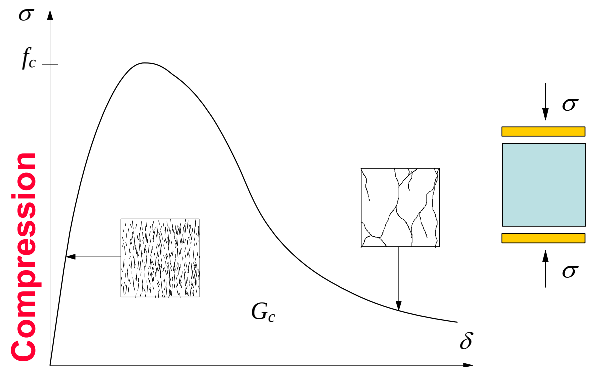


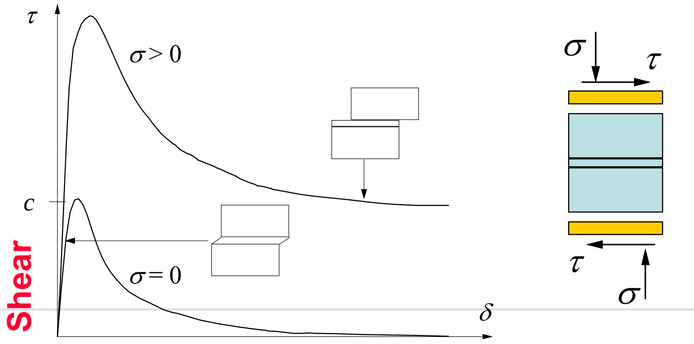
Possible cross section

Testing is available

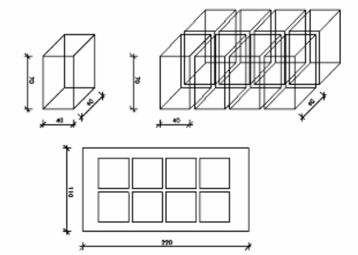
Aspects of Softening Behavior

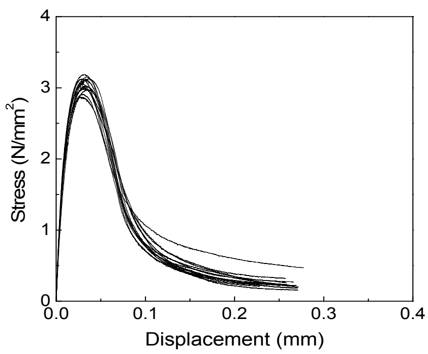




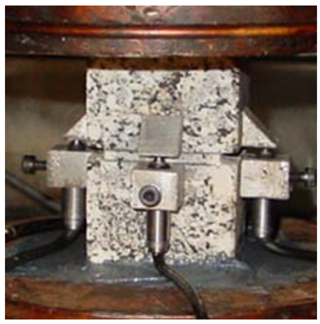


Tension





Typical results in solid bricks



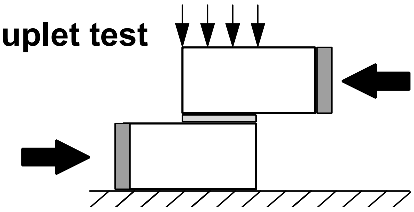
Stone

Portuguese Bricks:
- Tensile strength: 2.7 - 4.3 N/mm²
- Fracture energy: 0.05 - 0.09 N/mm²
- Slight anisotropy with higher strength along the extrusion direction
- High CV for the mechanical properties (30-70%), due to internal firing and shrinking cracks

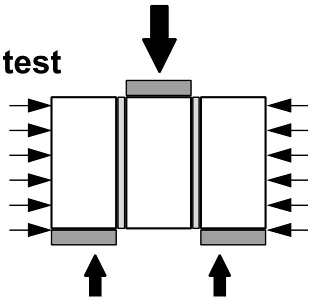
Portuguese Granites:
- Twelve lithotypes
- Tensile strength: 1.6 - 8.1 N/mm²
- Fracture energy: 0.15 - 0.27 N/mm²
- Anisotropy with rift plane and foliation

Properties of Unit-Mortar Interface – Shear

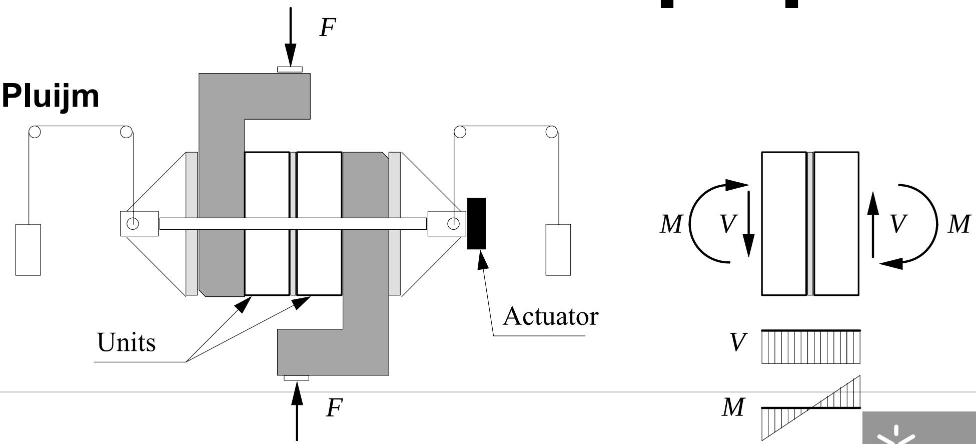
Couplet test



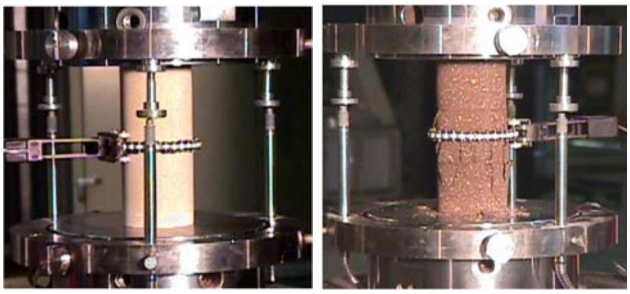
Triplet test



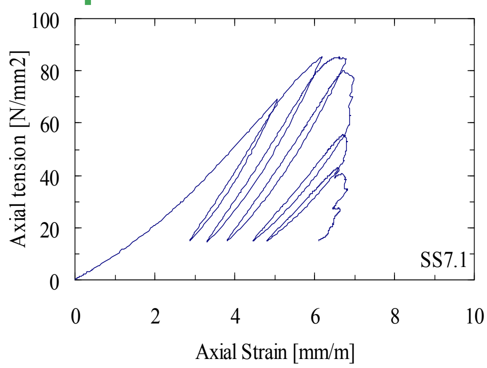
Van der Pluijm test



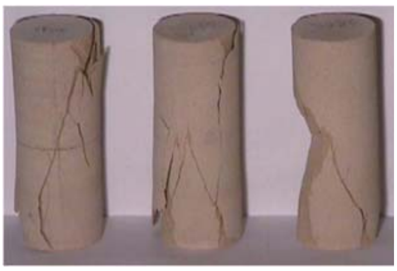
Composite Material – Uniaxial Compression



Sample

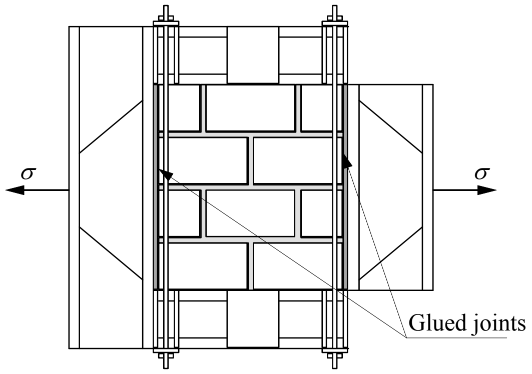


Stress-strain diagram

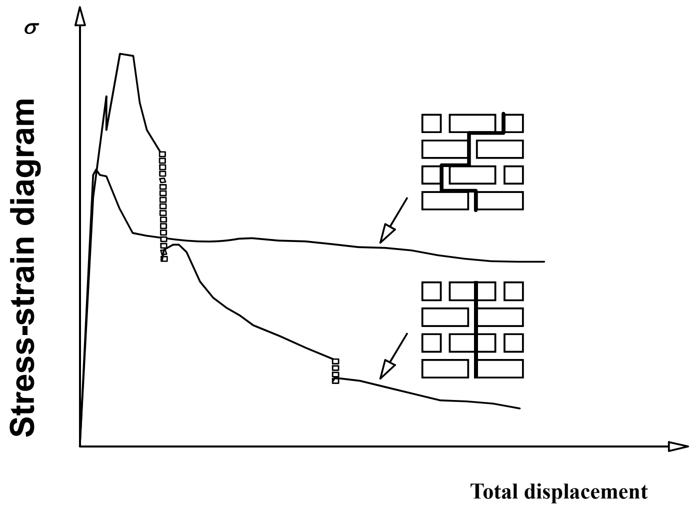


Failure

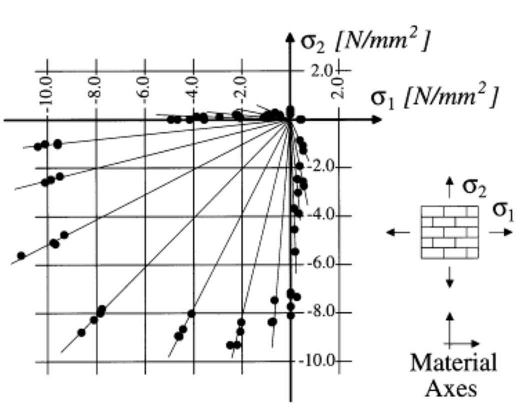
Composite Material – Uniaxial Tension



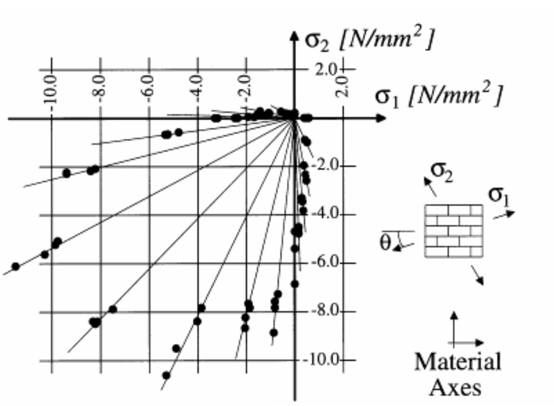
Specimen



Composite Material – Biaxial Behavior

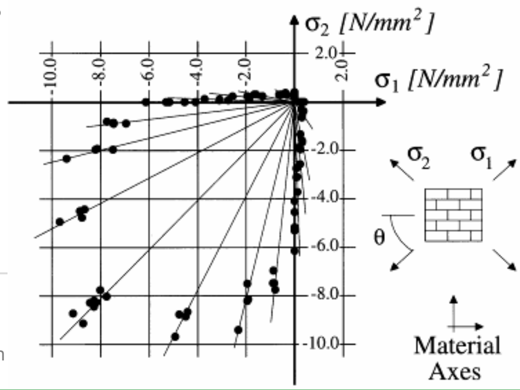


$\theta = 0^o$



$\theta = 22.5^o$

PAGE (1981, 1983)



$\theta = 45^o$

Data is available

Masonry Units

- Strong variability in old materials / Low variability in new materials

- Typical ancient masonry stones
  - Igneous – Granite (40 to 150 N/mm^2)
  - Sedimentary – Limestone (10 to 100 N/mm^2)
  - Metamorphic – Marble (30 to 150 N/m^2)
  - Metamorphic– Schist (5 to 60 N/mm^2)
  - Scatter in durability (In general stone is obtained from the upper part of the quarry = altered material)

- Clay brick in in ancient masonry
  - Thickness of 4 to 7 cm
  - Other dimensions are much variable (22 × 11 cm^2???)
  - Large porosity (20-35 %)
  - Low strength (5 to 20 N/mm^2)
  - Low durability (hand made; burnt in a traditional wood / coal kiln)

- Earthen units
  - Rather low strength (0.5 to 3 N/mm^2)

Masonry Mortars

- Modern mortars
  - Usually a thickness of 5 to 20 mm): Cement, Hydrated lime and Sand
  - Mix 1:3 (binders:sand) in volume is normally used
  - Glue mortar (thin bed) has much higher tensile bond strength
  - Strength is around 4 to 10 N/mm^2

- Ancient mortars
  - Mixes 1:2.5 and 1:2 are more usual
  - Hydrated lime means that hardening occurs only in contact with air
  - Addition of pozzolana or brick dust allows to create hydraulic products (i.e. capable of hardening under the water)
  - It is usual that mortars contain silty soil (50 to 100% of the aggregate)
  - Clay mortars and dry masonry are also usual
  - Strength is around 1 to 3 N/mm^2

  - A mortar of soil and lime needs to be "pressed" during the curing process
  - For repointing / substitution the color of the silty soil / stone dust / aggregate allows to tune the final mortar color (typically white)
  - A mix composition with a small percentage of white cement is sometimes used in restoration activities

Masonry Composite (I)

- Compressive masonry values – Design Values. Recommendations PIET-70

Stone type	Stone strength [N/mm^2]	Ashlar masonry			Other masonry		
		Dry, with good adjustment between faces	Ashlars h > 0.30m Mortar > M8	Ashlars h < 0.30m Mortar > M4	With well defined courses Mortar > M4	Irregular Mortar > M0.5	Dry
-Granite -Basalt	>100	8.0	6.0	4.0	2.5	1.0	0.7
-Quartz sandstone -Hard limestone -Marble	>30	4.0	3.0	2.0	1.2	0.8	0.6
-Lime sandstone -Soft limestone	>10	2.0	1.5	1.0	0.8	0.6	0.5

Masonry Composite (II)

❑ Compressive masonry values

Italian code

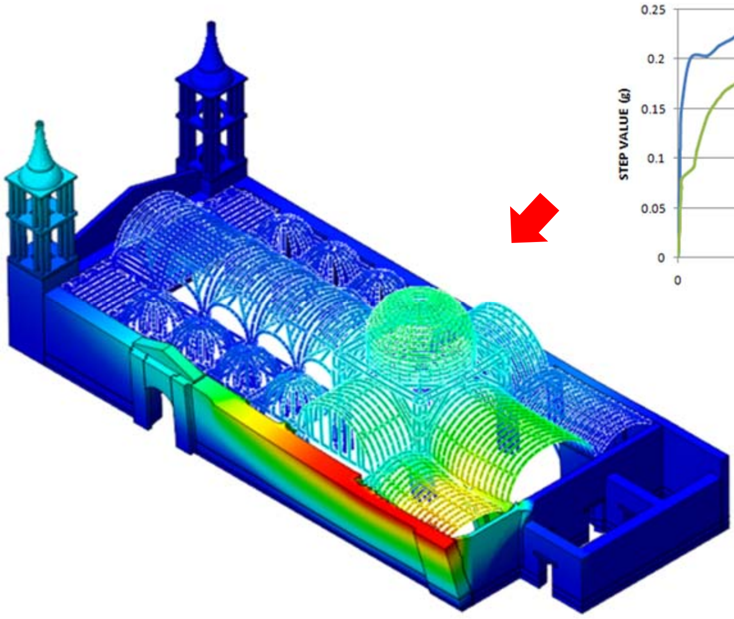
f_m = average compressive strength of masonry
τ_0 = average shear strength of masonry
E = average value of the normal elastic modulus
G = average value of the shear modulus
w = average specific weight of the masonry

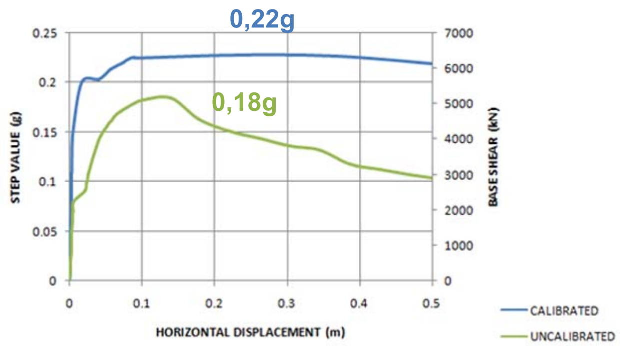
Table 11.D.1: Reference values of the mechanical parameters (maxima and minima) and average specific weights for different types of masonry related to the following conditions: poor quality mortar, absence of courses (coursed masonry at regular intervals), wall leaves merely placed together or badly connected, unconsolidated masonry.

Masonry typology	f_m (N/cm^2) min-max	τ_0 (N/cm^2) min-max	E (N/mm^2) min-max	G (N/mm^2) min-max	W (kN/m^3)
Irregular stone masonry (pebbles, erratic and irregular stone)	60 90	2.0 3.2	690 1050	115 175	19
Uncut stone masonry with facing walls of limited thickness and infill core	110 155	3.5 5.1	1020 1440	170 240	20
Cut stone masonry with good bonding	150 200	5.6 7.4	1500 1980	250 330	21
Soft stone masonry (tuff, limestone, etc.)	80 120	2.8 4.2	900 1260	150 210	16
Dressed rectangular stone masonry	300 400	7.8 9.8	2340 2820	390 470	22
Full brick masonry with lime mortar	180 280	6.0 9.2	1800 2400	300 400	18
Masonry in half-filled brick blocks with cement mortar (e.g. double UNI)	380 500	24.0 32.0	2800 3600	560 720	15
Hollow brick masonry (percentage of perforations < 45%)	460 600	30.0 40.0	3400 4400	680 880	12
Hollow brick masonry with dry perpend joints (percentage of perforations < 45%)	300 400	10.0 13.0	2580 3300	430 550	11
Concrete block masonry (percentage of perforations between 45% and 65%)	150 200	9.5 12.5	2200 2800	440 560	12
Masonry in half-filled concrete blocks	300 440	18.0 24.0	2700 3500	540 700	14

Sensitivity analysis

Ica Cathedral, Peru





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Step 2: Model Masonry

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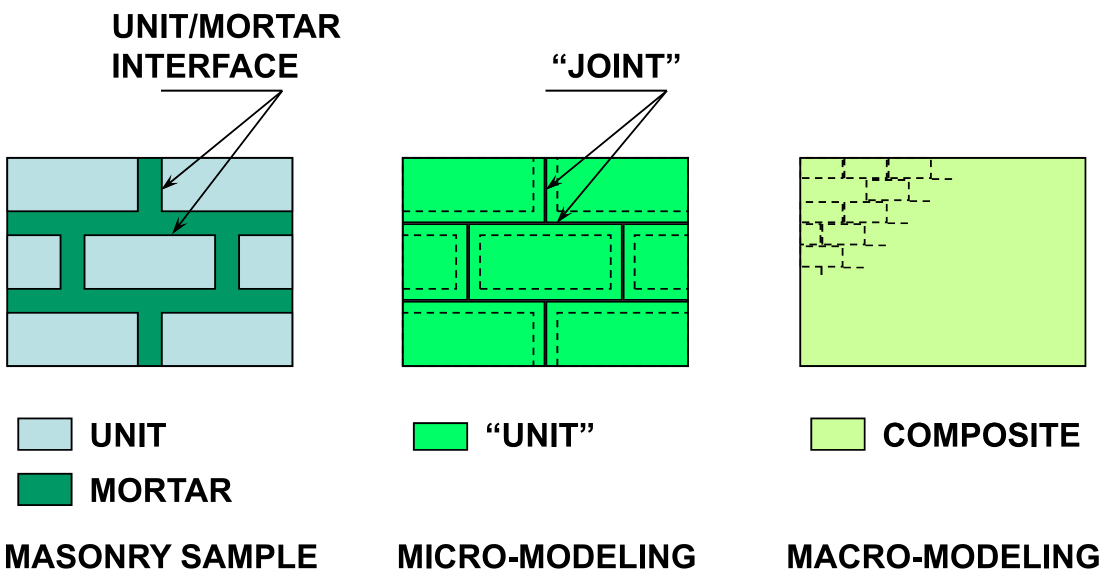
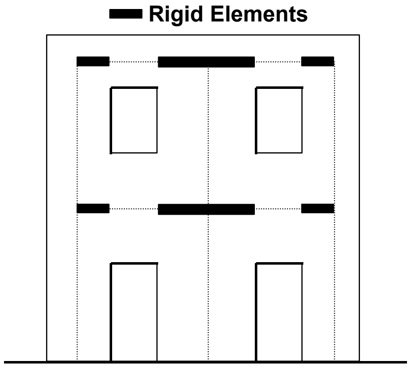
General remark

- Recent advances are very significant
- The methods available use different theories and approaches, resulting in:
  - Different complexity levels
  - Different access for practitioners
  - Different costs
- The key aspects to be considered in the decision about the most adequate analysis tool depend on:
  - The relation between the analysis tool and the sought information
  - Available tools to use in the project (it is of capital importance that the designer fully understands the analysis tool)
  - Costs, available resources and time for analysis

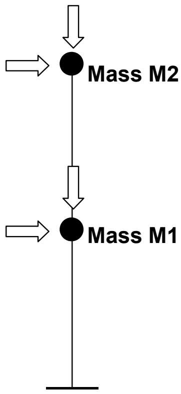
Modeling Approaches – Material Level



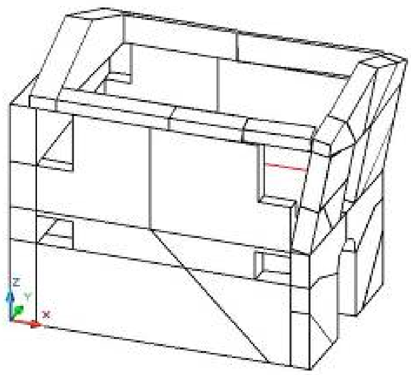
Modeling Approaches – Structural Level (I)



Beam elements model



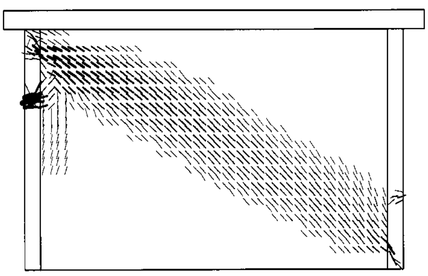
3-degree of freedom model



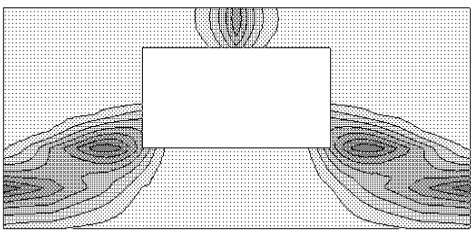
Macro-block model

STRUCTURAL COMPONENT MODELS

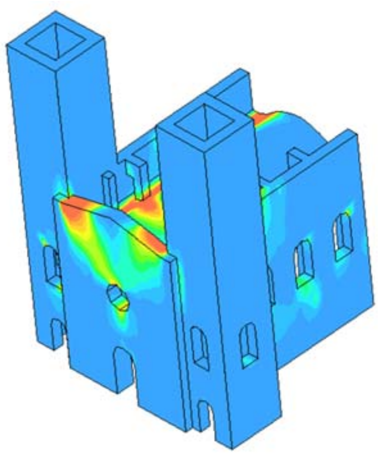
Modeling Approaches – Structural Level (II)



Shear wall



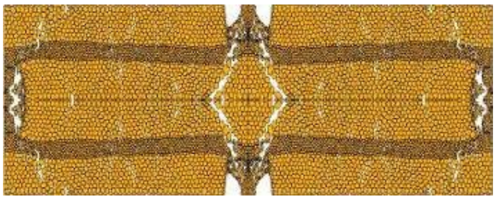
Wall with out of plane behavior



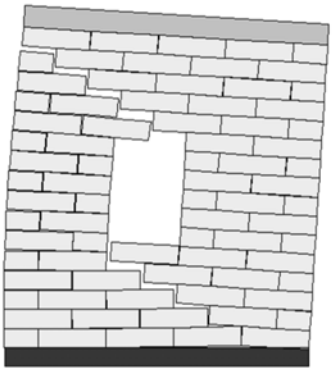
Church Settlements

STRUCTURAL MACRO-MODELING / FINITE ELEMENT METHOD

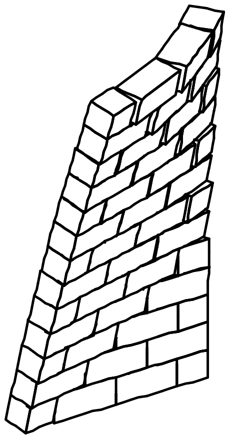
Modeling Approaches – Structural Level (III)



Masonry compressive failure



Shear wall (in plane behavior)



Wall with out of plane behavior

STRUCTURAL MICRO-MODELING / FEM, DEM, LIMIT ANALYSIS

Analysis approaches

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

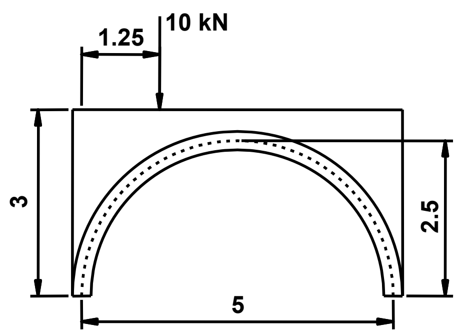
- ❑ Linear elastic time history analysis
- ❑ Modal superposition
- ❑ Linear static analysis

Simplification

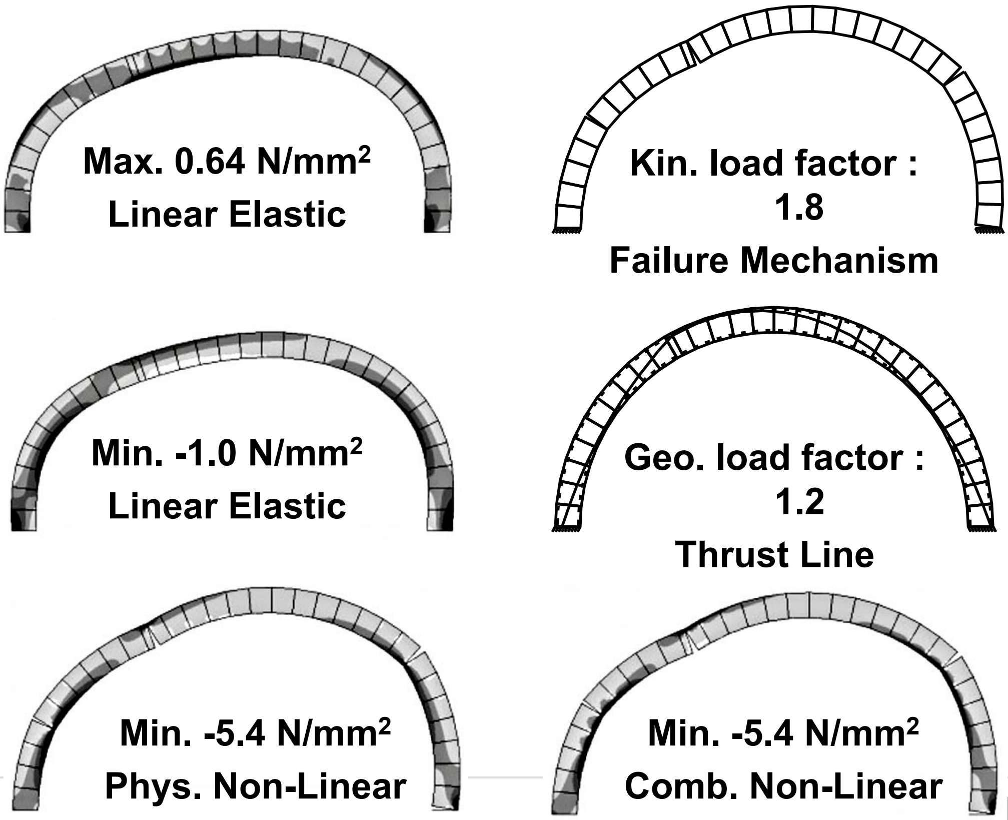
DIFFERENT MODELS = DIFFERENT RESULTS ???

Static Analysis Methods (I)

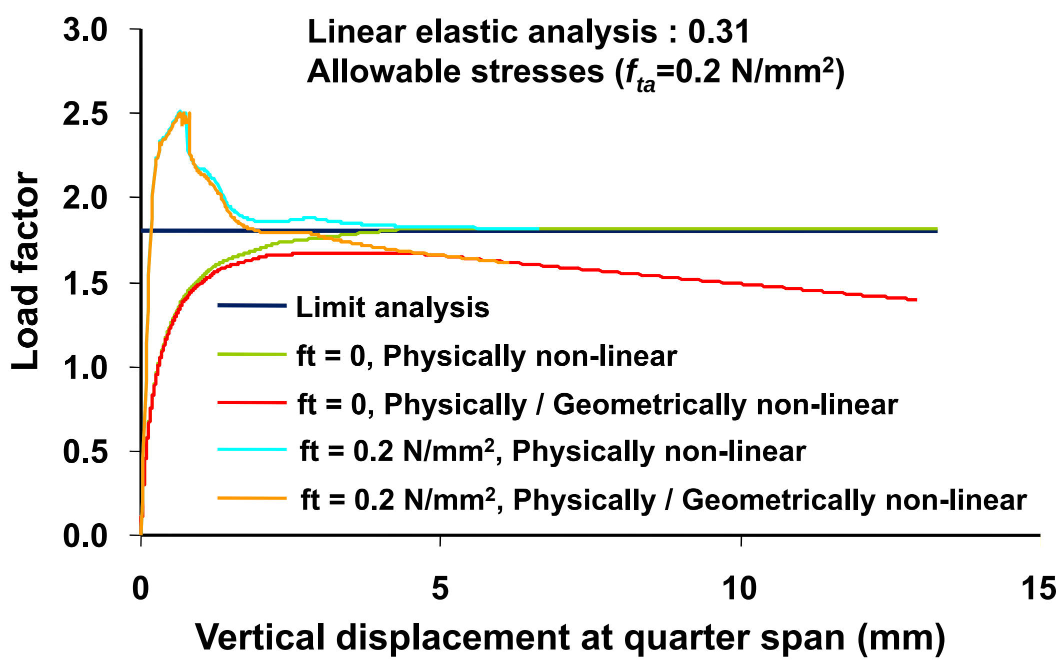
- **Linear Elastic Analysis**
  elastic properties + maximum admissible stress
- **Kinematic Collapse Mechanism Analysis**
  inelastic properties = friction angle + tensile and compressive strengths
- **Static Thrust Line Analysis**
- **Non-linear Analysis (Physical and Combined)**
  FULL inelastic properties (ft = 0 and ft ≈ 0) + elastic properties



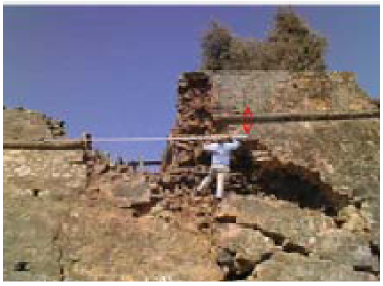
Static Analysis Methods (II)

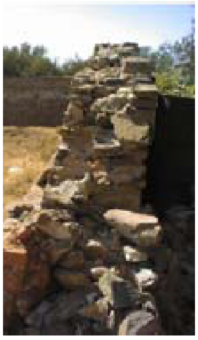


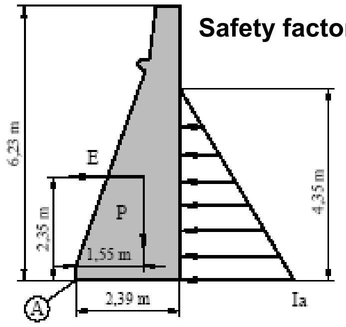
Static Analysis Methods (III)



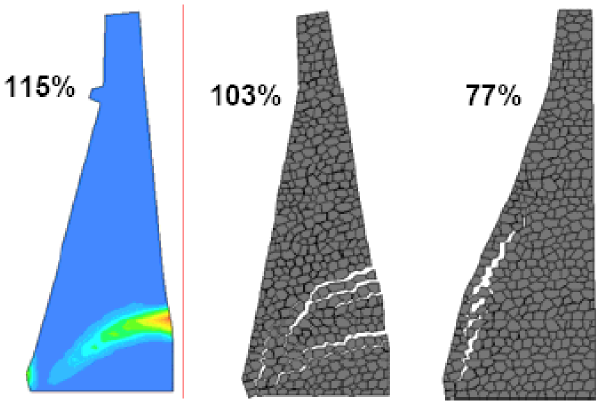
Example 2:







Safety factor: 124%

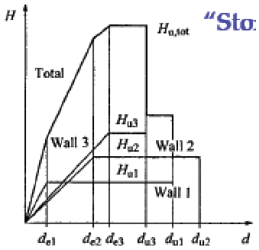


Example 3: Rigid diaphragm

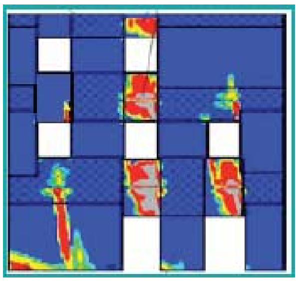
- Worst case scenario: Embedded ring beam + Unfilled vertical joints
- Moderate damage up to 100% of the design earthquake in Lisbon
- Ductile failure for 250% of the design earthquake in Lisbon

Advanced structural analysis techniques

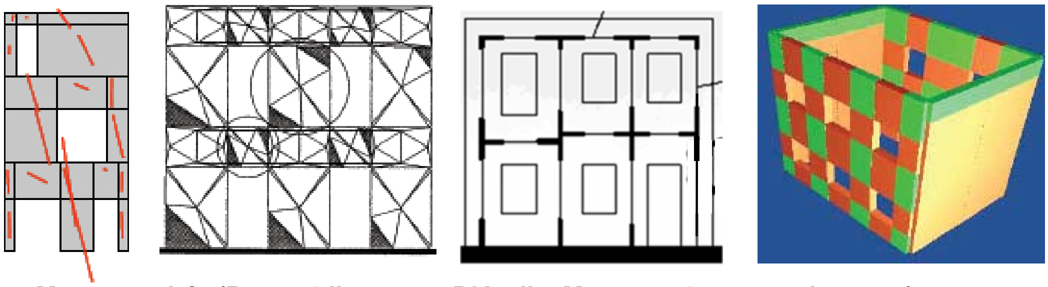
- Elastic analysis is unreasonable
- Many non-linear approaches can be used
- Provide very good results
- Knowledge is stabilized



"Storey" model (Por)
Tomazevic

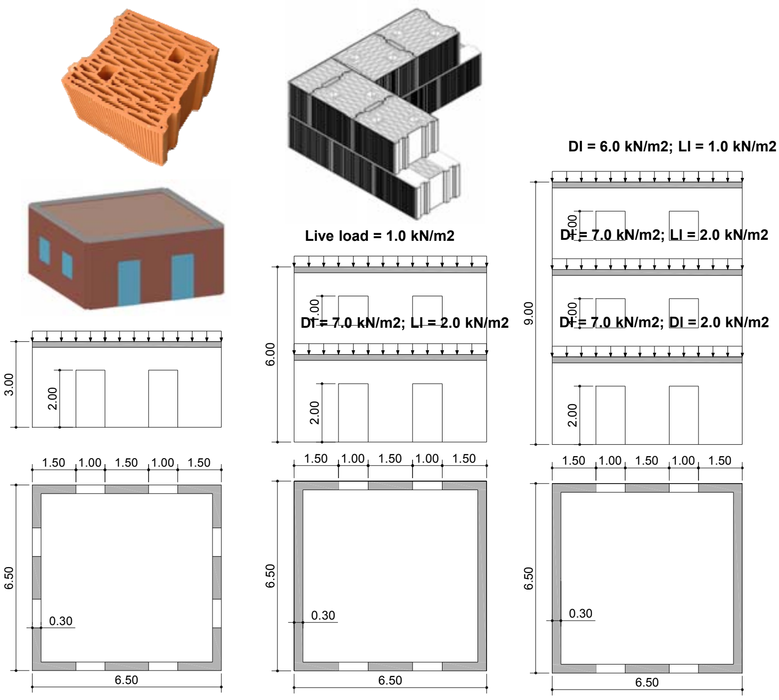


Finite element model
(Many authors)



Macro-models (Braga, Liberatore, D'Asdia, Magenes, Lagomarsino, etc.)

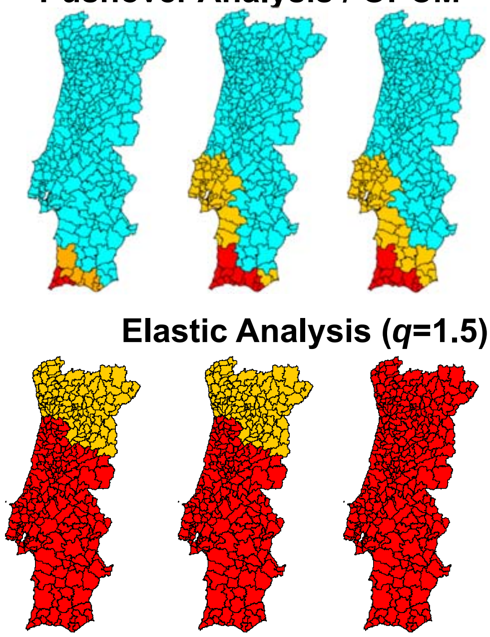
Use the right analysis method!



1 storey 2 storeys 3 storeys

Pushover Analysis / OPCM

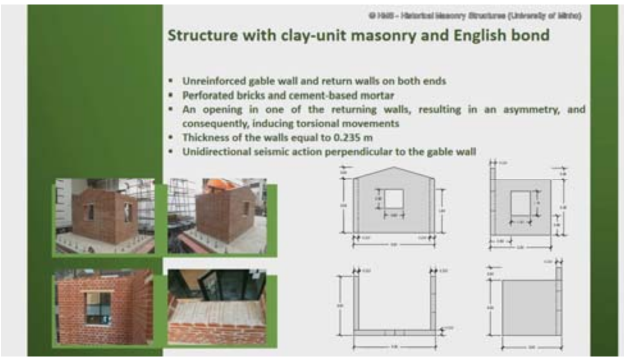
Elastic Analysis (q=1.5)

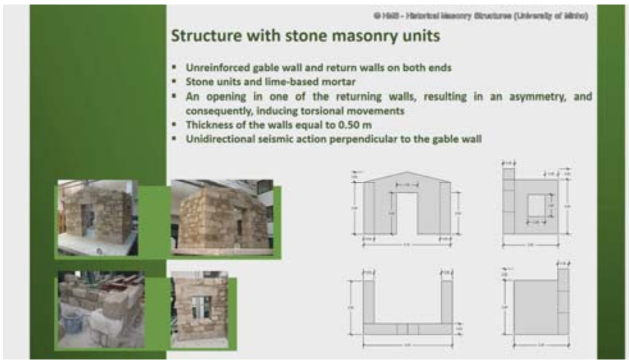


Cannot be used
Can be used for hard soils
Can be used for good soils

Example 4: Existing masonry buildings without rigid diaphragm

- ❑ Recent benchmark test
- ❑ 25 international masonry experts
- ❑ 18 blind predictions
- ❑ 2 masonry types





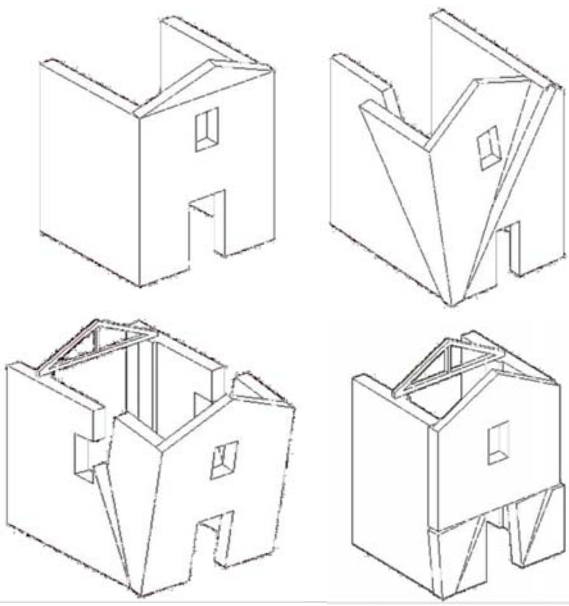
Absence of box behavior. Study by macro-elements

- ❑ **Assume that no expulsive type of failure exists and assume portions of the buildings with homogeneous constructive characteristics and structural behaviour.**

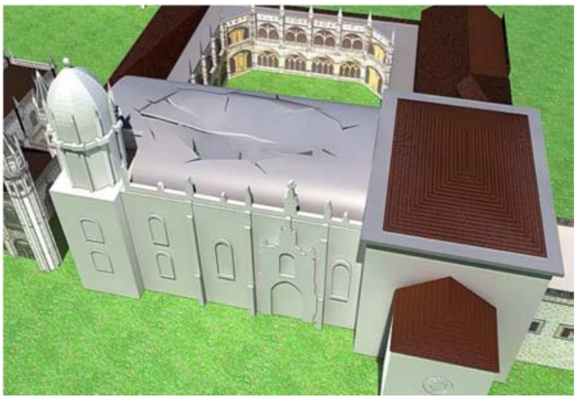
1- Individuation of collapse mechanisms on the bases of abacuses of typical damage

2- Schematization of the mechanisms by means of kinematics models, based on equilibrium condition

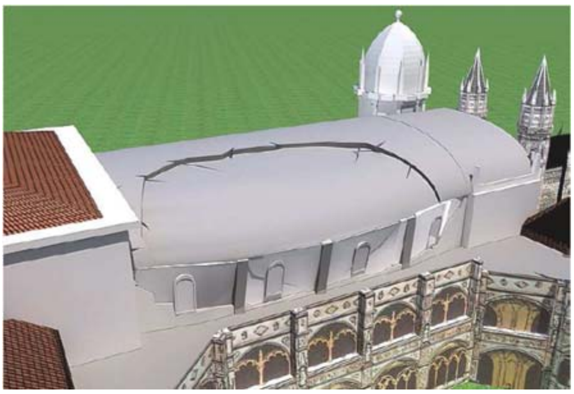
3- Calculate C = a / g for the elementary mechanism, i.e. the seismic mass multiplier that leads the element to failure



Virtual Collapse Mechanisms



Vertical loading



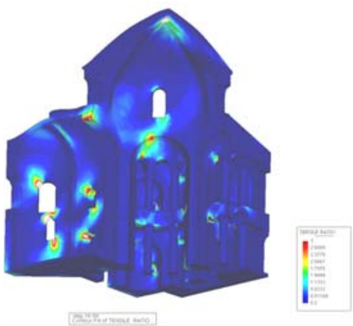
North façade

South façade

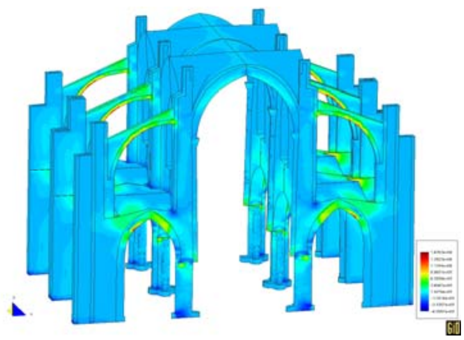
Final Remarks

Universidade do Minho

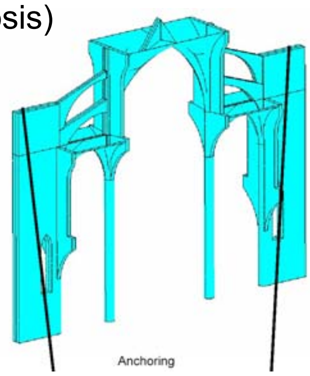
The role of structural analysis



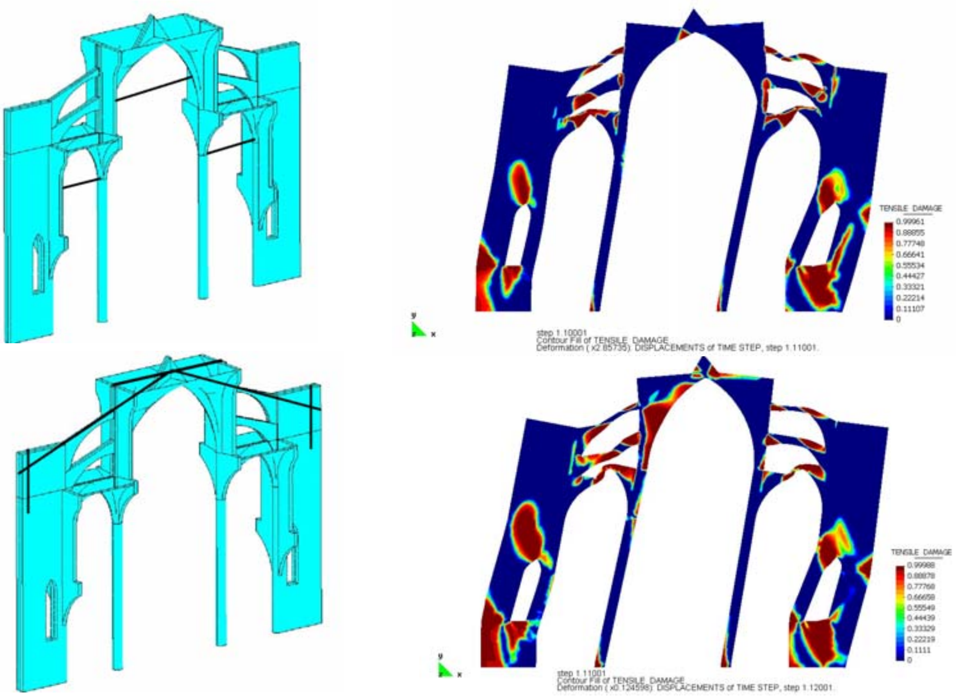
Contribution to diagnosis
(+ history, inspection, diagnosis)



Contribution to safety evaluation

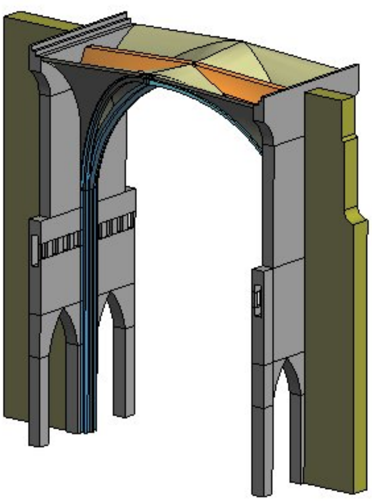


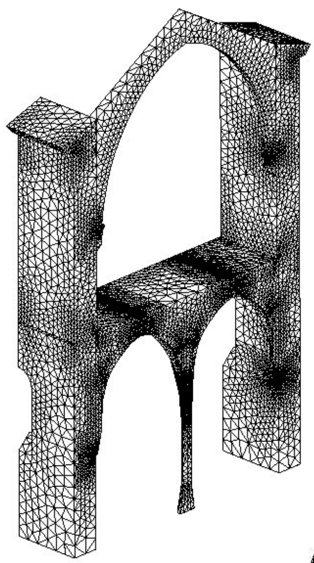
Contribution to design /
validation of intervention

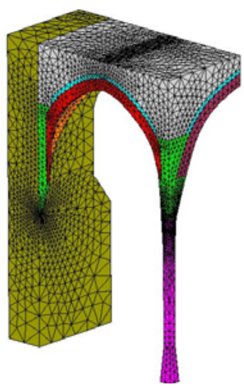


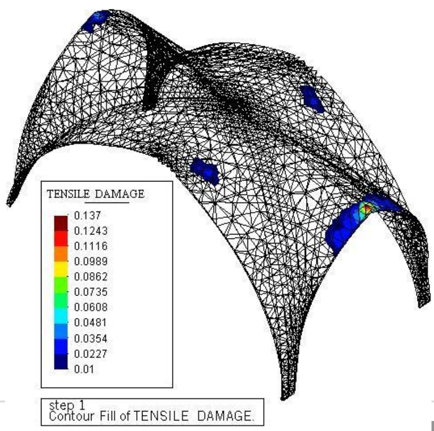
Simulation of two alternative strategies to strengthen a Gothic church

Numerical models









The response of the structure is simulated by means of mathematical formulation implemented in a computer code

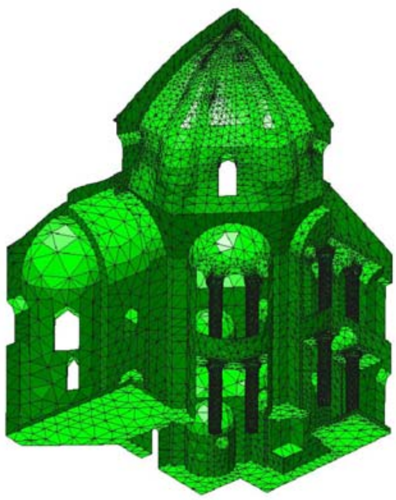
Requirements

- Ability to explain past or present observations
- Ability to predict future observations
- Refutability, enabling estimation of the degree of confidence
- To possible extent, simplicity
- Input data obtainable by means of available, reasonably inexpensive in situ or laboratory inspection / experimental procedures, or experience / recommendations
- Adequately representing, at least, the phenomena that are targeted

Model as recipient of hypotheses

(1) the conceptual decision what phenomena the model should represent / take into account

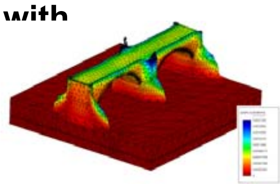
(2) specific quantities related to material, geometrical, morphological properties of a specific building



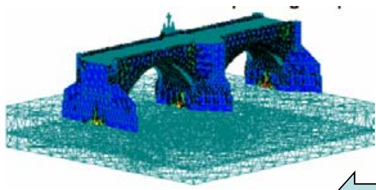
The model must be calibrated and validated by comparison with empirical / experimental information on the response of the building

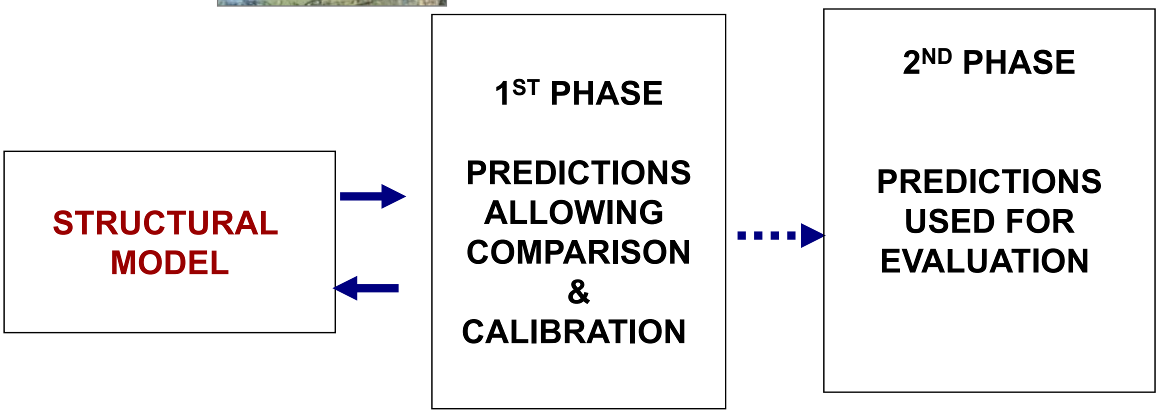
Scientific use of numerical analysis - procedure

1. Construct modeling hypothesis
2. Calibrate/identify the model
3. Use the model to reproduce state/behavior of the of the structure that is known – compare result with reality



4. Not OK? – refine model
5. Use model for evaluation safety, prediction of behavior, design ... in addition to other resources





Once the model is validated (1st phase) , it will be to predict unknown aspects of the structural response. For instance, the model could be validated for dead loading (known response) and then be used to predict the seismic capacity (otherwise unknown)

CHALLENGES (1) - THE MATERIAL

Historical / traditional materials (earth, stone, masonry, wood) are characterized by very complex mechanical and strength phenomena still challenging our modeling abilities.

In particular, masonry is characterized by

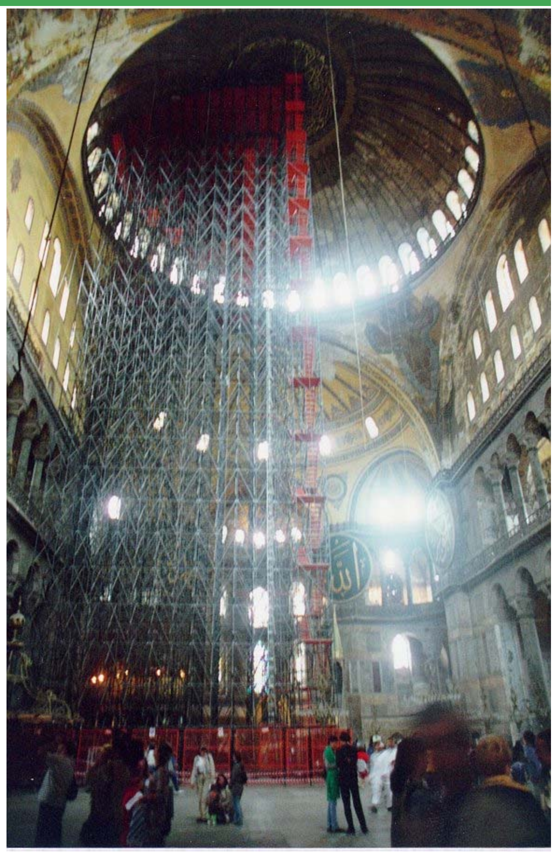
- composite character (stone / brick & mortar)
- brittle response in tension (almost null tensile strength)
- frictional response in shear (once the limited bond between units and mortar is lost)
- anisotropy (response depends with the orientation of loads)

CHALLENGES (2) - THE GEOMETRY

Historical structures show a very complex geometry. They often include straight (pillars) or curved (arches) members. They combine curved 1D members (arches, flying arches) with 2D members (vaults, domes) and 3D ones (fillings, pendentives…). They combine slender members with massive ones (massive piers, walls buttresses, foundations…).

Even if still a challenge, today numerical methods (such as FEM) do afford a realistic and accurate description of geometry.

Geodetic methods may be used to acquire actual geometry.



CHALLENGES (3) - MORPHOLOGY AND CONNECTIONS

Structural members are often non-homogeneous but show an internal structure including several layers, filling, material, cavities, strengthening insertions…

Connections are singular regions featuring specific geometric and morphological treats. The transference of forces may activate specific resisting phenomena (contact problems, friction, eccentric loading).

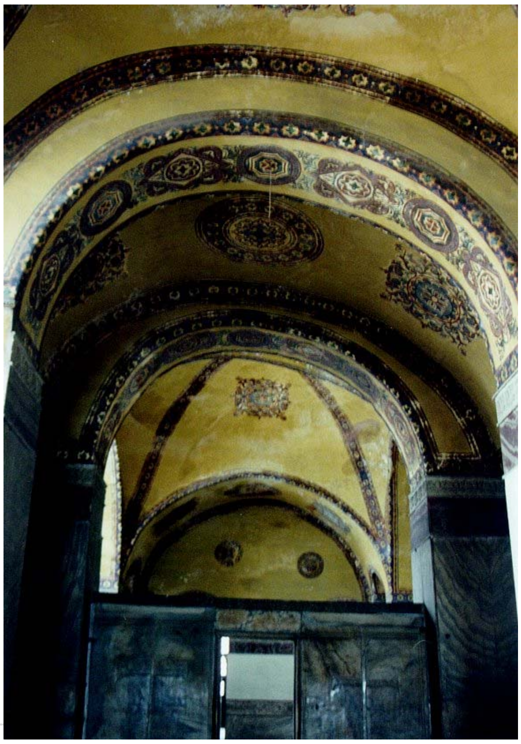
Modeling morphology and connections in detail may be extremely demanding from a computational point of view. Nevertheless, the main difficulty is found in physically characterizing them by means of minor- or non-destructive procedures.

CHALLENGES (4) ACTIONS

Historical structures may have experienced (and keep on experiencing) actions of very different nature. They are to be characterized in historical time. Some are cyclic and repetitive (and accumulate significant effects in the long term), some develop gradually in very long time periods, some are associated to long return periods…

Gravity loading
Long-term damage of mechanical nature (creep?)
Settlements
Thermal cycles and micro-tremors (multiple repetitions in historical times)
Major earthquakes
Fires, accidents
Alterations, inadequate restorations
Biological, chemical attack…

CHALLENGES (5) - REAL CONDITION



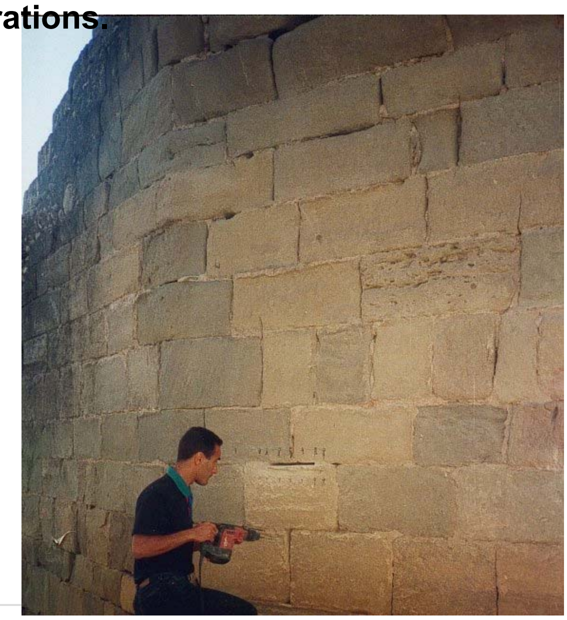
Realism and accuracy require the model to include or simulate existing damage and alterations (at, least, those which may affect the structural performance).

Main cracks and deformation should be included in the model. Cracks, for instance, may be modeled by disconnecting some elements or by weakening the mechanical and strength properties of the regions affected.

Damage involves cracking, decayed material (due to chemical or physical attack) or whatever phenomena causing a reduction of the original capacity of materials and structural members.

CHALLENGES (6) - DATA

Historical materials and structures are normally very heterogeneous and their properties show large scattering. Structures are also affected by many additions (using different materials) and alterations.



Data acquisition is limited because of the due respect to the monument and original material.
Non- destructive, indirect, tests and minor destructive tests are preferred. If any, only a very limited number of pits allowing direct observation is normally acceptable.

In practice, only limited and partial information can be collected. Additional assumptions on morphology and material properties may be needed in order to elaborate a model.

CHALLENGES (7) - HISTORY

History is an extremely important feature of the building and must be considered and integrated in the model. The following effects linked to history may have had influence on the structural response and existing damage:

Construction process
Later architectural alterations, additions…
Destruction in occasion of conflicts (wars…)
Historical natural actions (earthquake, floods, fires…)
Long-term damage phenomena

However, history constitutes also a source of knowledge. The historical performance of the building, if knowable, can be engineered to draw conclusions on the structural strength and weakenesses. As already mentioned, the history of the building constitutes a precious experiment occurred in true scale of space and time. In a way, history makes up for the aforementioned data insufficiency.

Applications (I): Models of capital importance

Monastery of Jerónimos

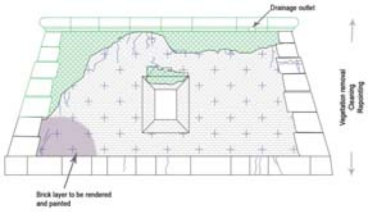
Monastery of Salzedas

Cathedral of Porto

Convent of Tomar

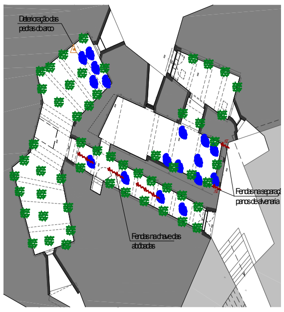
Applications (II): Models of capital importance

Qutb Minar, New Deli, India



Pontifical defense, Italy

Canterbury cathedral, UK



Safi and Mazagan, Morocco

Famagusta Cyprus

Mashad, Iran

Conclusions

Conclusions & Prospects

- ❑ Advanced tools for masonry structural analysis are available. Information on advances material data is increasingly available.
- ❑ Understand the experimental behavior of masonry before modelling it
- ❑ Understand what you are doing when carrying out advanced numerical analysis: do not use FEM software as a “black-box”
- ❑ There is a need for validation of models. Check results of complex analyses against simple/engineering estimates
- ❑ Do not use linear elastic analysis for masonry under earthquake loading. Pushover analysis can be used for assessment, even if it is not easily available to practitioners. Abacus for macro-block limit analysis are available, leading to practice oriented assessment and strengthening design (part 2)

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P.S.

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Learning from Bohol site visit

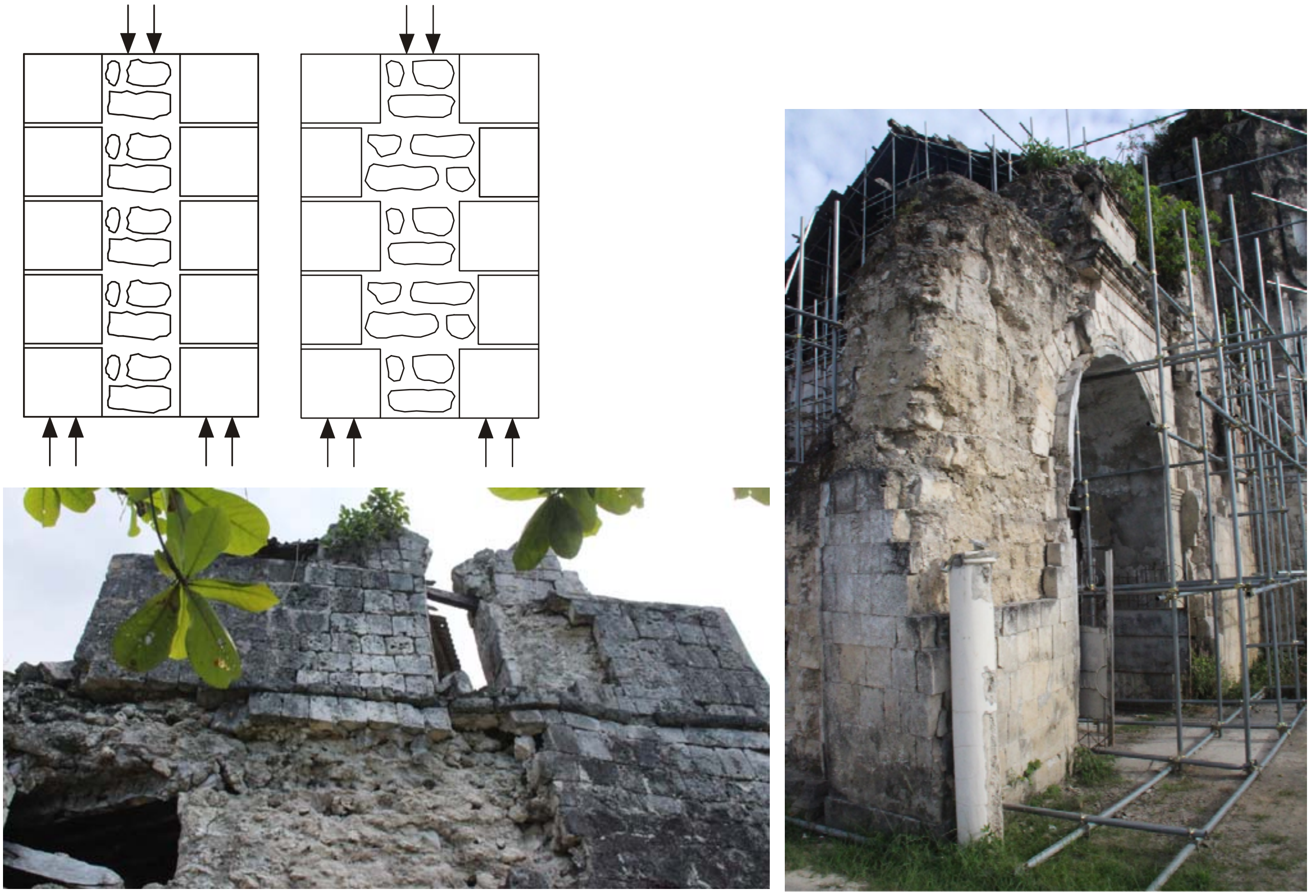
Excellent seismic local culture: St. Dimiao Church

- Thick walls (large width to height ratio)
- Multiple ties in floors and roof. Timber keys, internally and externally, as well as corner keys
- Globally, a good performance, except untied walls


In general, no seismic culture. Problems:

- Sometimes deficient overlap of masonry units (inadequate bond)
- Insufficient connection between external leave and inner core
- Poor connection between orthogonal walls
- Insufficient number of ties (and absence of timber keys). Possibly inadequate roof solutions for tying parallel walls
- Transept mostly unconfined by arches (in arms, nave and chancel)? They seem a highly vulnerable part
- Lack of protection measures from rain (after the earthquake, at least). Need to place tarp protection

No staggering of units



No connection of the external leave to the inner core

Lack of connection between transverse walls

Absence of protection to rain, uncontrolled growth of vegetation

Good news for Bohol:

- Good quality mortar
- Solid and good quality inner core
- Availability of lime
- Likely availability of timber

Needs for Bohol:

- Improve connections (roof and floors to walls; corner keys in the walls; buttresses if needed)
- Check transept vulnerability
- Assume that external masonry layer might need to be repaired after a strong shake? Pinning?

Analysis Methods for Unreinforced Heritage Masonry (I): Masonry Behavior and Modeling

isise

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