Detailed and simplified non-linear models for timber-framed masonry structures

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(Based on PhD work by L.-A. Kouris)

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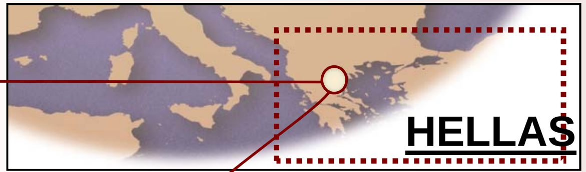

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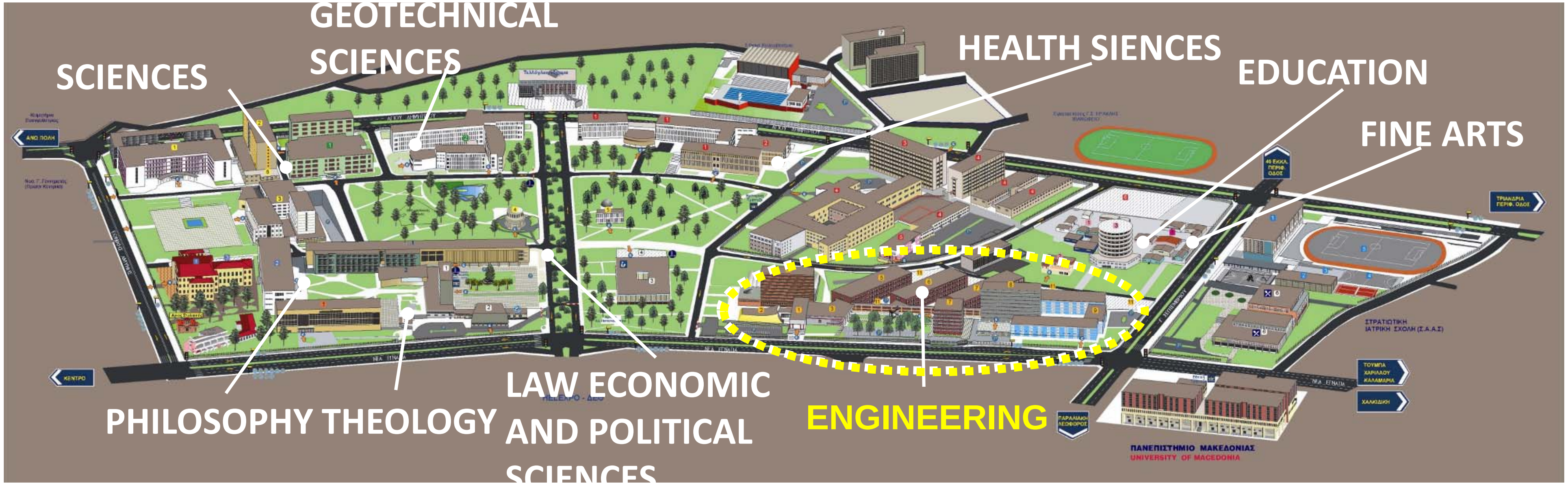

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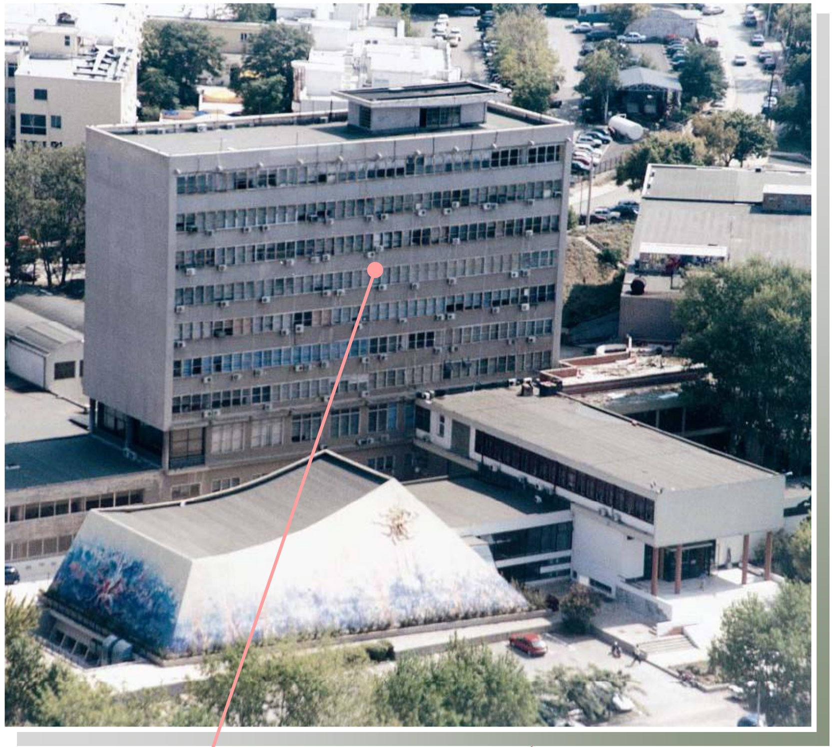
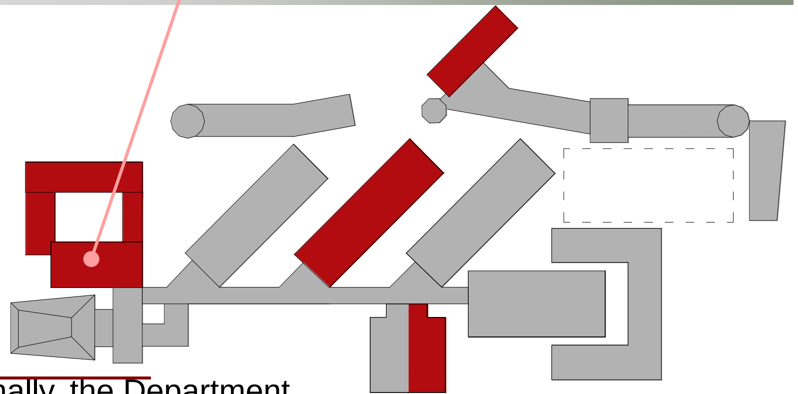




Timber framed construction in the course of history

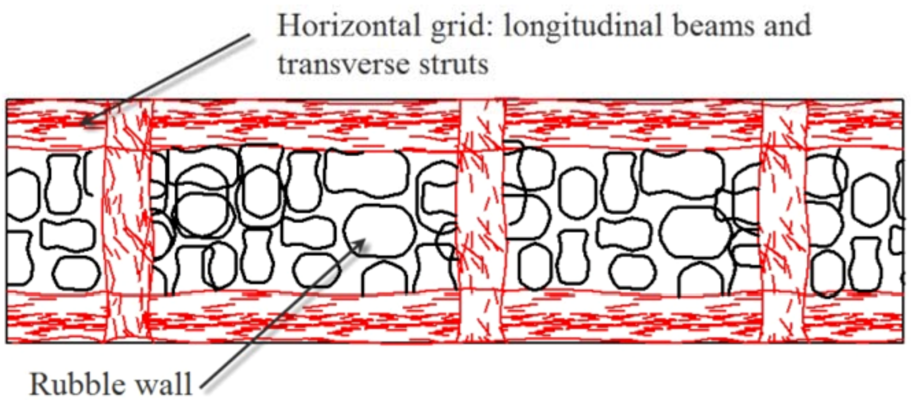
Bronze Age | Ancient Greek and Greek-Roman Times | Medieval Centuries | Nowadays

- Remains of T-F masonry buildings since the Bronze Age in: Minoan Crete, Mycenae, and the island of Thera.

Timber framed construction in the course of history

Salient features:

- Low degree of sophistication; a few vertical and/or horizontal elements → no diagonals (braces).
- One timber framework on each face of the thick masonry wall.
- Used only in critical parts of the building.
  - In crossing walls joining them at the corners.

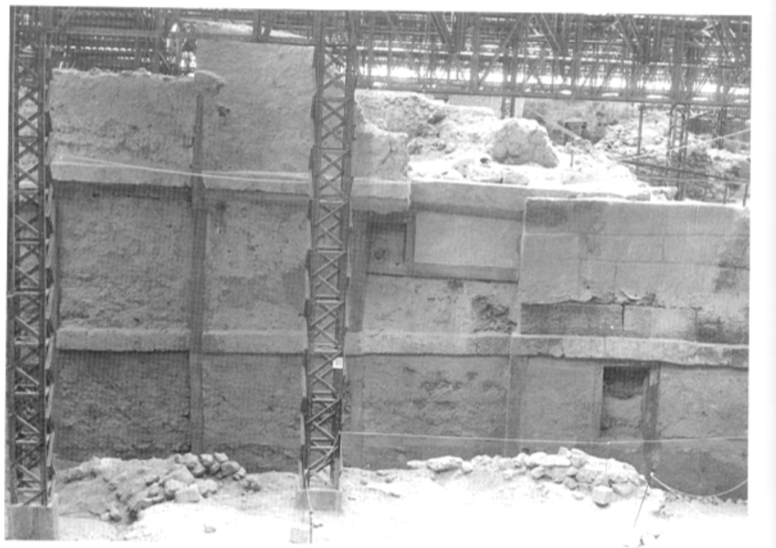


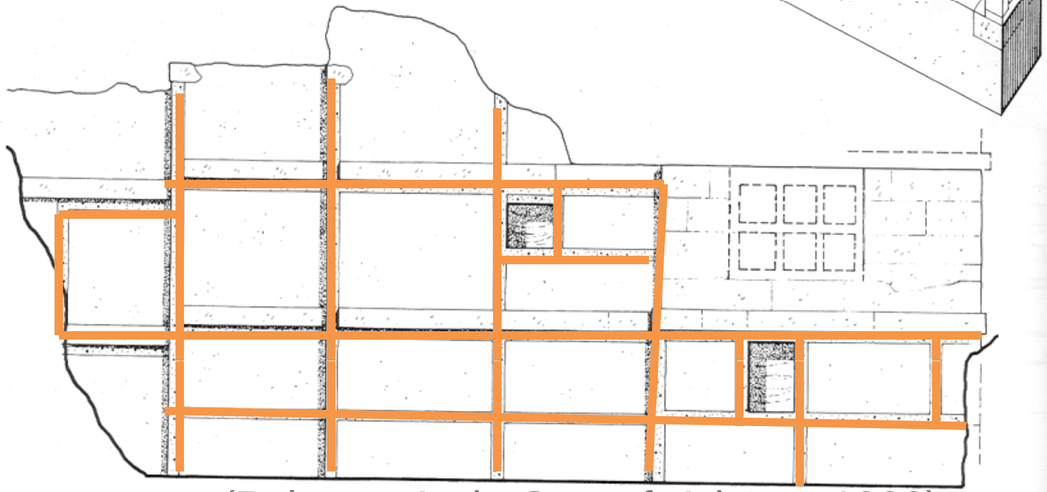
Timber framed construction in the course of history

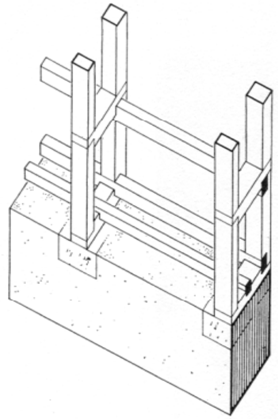
Bronze Age | Ancient Greek and Greek-Roman Times | Medieval Centuries | Nowadays

A complete T-F masonry system:

- found in Thera; 7m high remains of the 3-story building Xeste-2.
- ordinary wooden frames with masonry infill (but no diagonals).
- section of timber elements; 20 cm square.
- vertical spacing about 0.8 m.





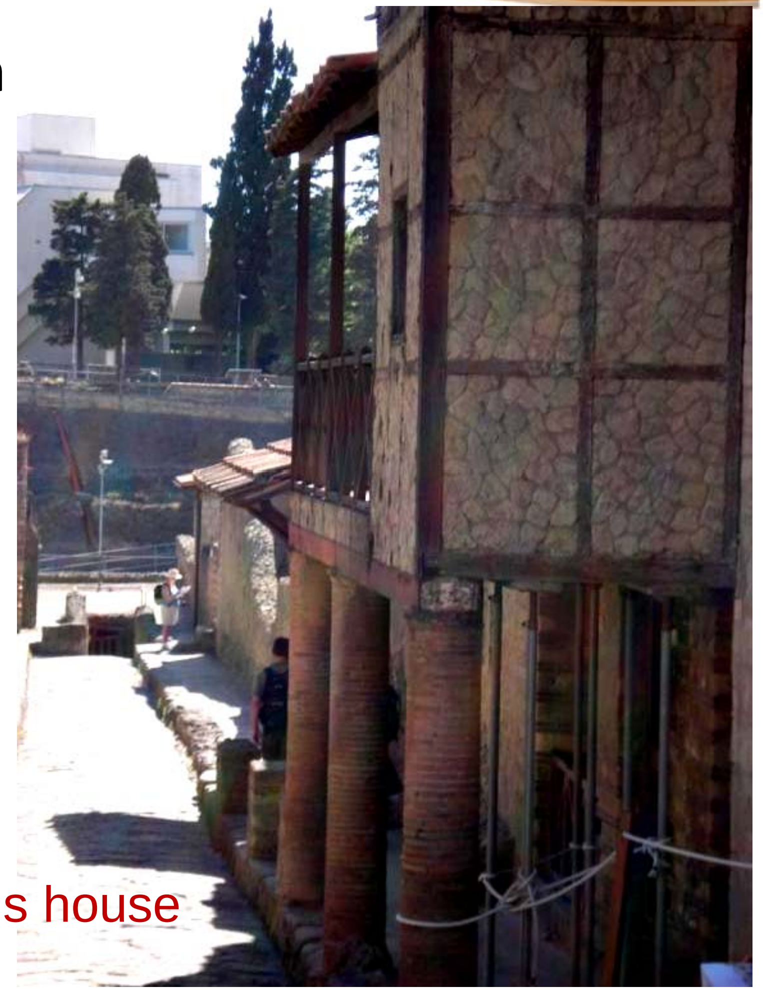


(Palyvou, Arch. Soc. of Athens, 1999)

Timber framed construction in the course of history

Bronze Age | **Ancient Greek and Roman Times** | Medieval Centuries | Nowadays

- In the town of Herculaneum, buried in the lava from the Vesuvius volcano in 79 AD, single-leaf T-F masonry buildings were found
- Vitruvius called this type of stucture "Opus Craticium".
- Timber elements have square cross-section with side 10~12cm and form panels of 1×1m.

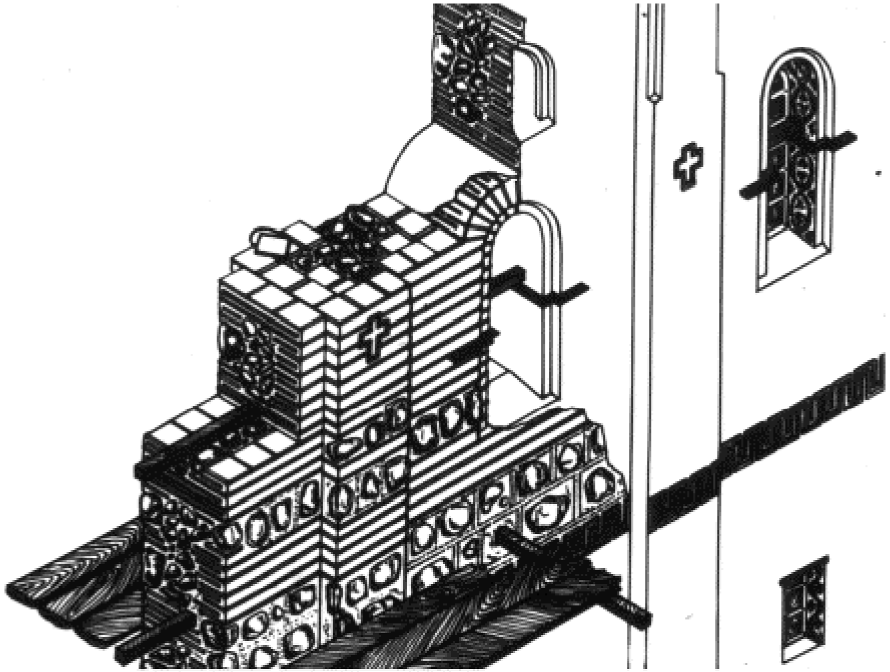


the Trellis house

Timber framed construction in the course of history

Bronze Age | Ancient Greek and Greek-Roman Times | **Middle Ages** | Nowadays

- Horizontal timber elements incorporated in masonry walls were commonly used in Byzantine churches, defense walls and other large stuctures.



(Moropoulou et al., SDEE, 2000)

Timber framed construction in the course of history

Bronze Age | Ancient Greek and Greek-Roman Times | 16th -19th century | Nowadays

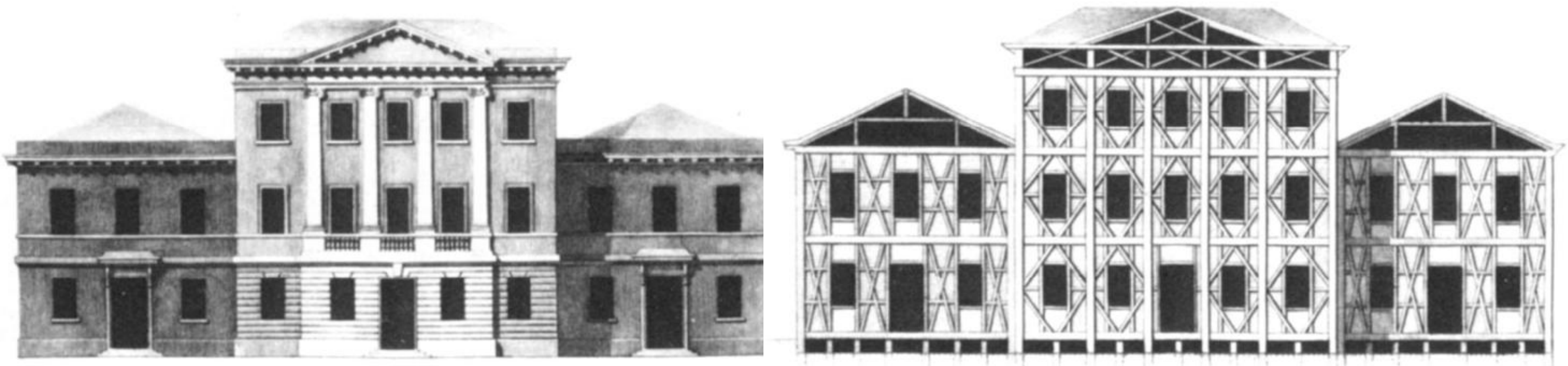
- Timber-framed masonry was used as an earthquake-resistant structure at least since the 18th century in seismic-prone areas.
- In some interesting cases it was introduced as a preventive measure after strong seismic events.

- After the 1755 catastrophic earthquake, the centre of Lisbon was rebuilt with new provisions: T-F masonry was used to enhance seismic capacity. The ‘Pombalino’ = the external masonry façade + an internal timber frame (‘gaiola’).

Timber framed construction in the course of history

Bronze Age | Ancient Greek and Greek-Roman Times | **16th -19th century** | Nowadays

- In Calabria (S. Italy), after a strong seismic sequence in 1783 the local government decided the reconstruction of the earthquake-striken area with timber-framed masonry buildings (‘Casa Baraccata’).
- Casa Baraccata also consisted of a wooden internal frame with diagonal braces invisible from the outside and the external masonry wall, connected to each other (‘dual’ system).



(Tobriner, The Journal of the Soc. of Arch. Historians, 1983)

Timber framed construction in the course of history

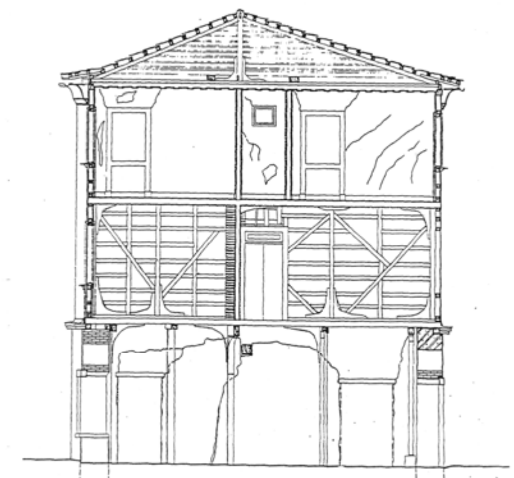
Bronze Age | Ancient Greek and Greek-Roman Times | 16th -19th century | Nowadays

- Another timber-framed masonry system is found in Lefkas, Greece in which the dual system consists of the ground stone-masonry floor and the upper timber-framed storeys.

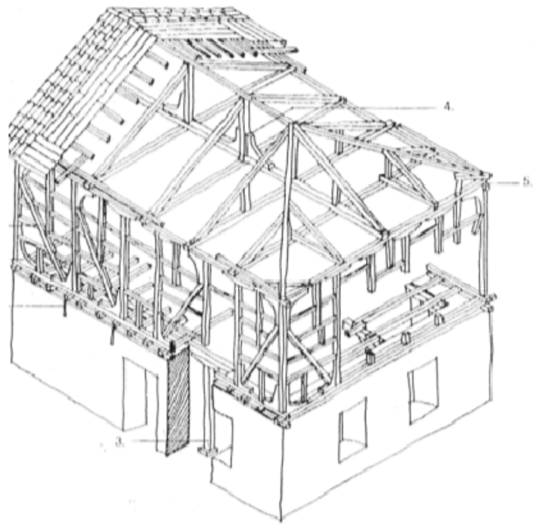
(Touliatos, NTUA, 1995)

Timber framed construction in the course of history

- Lefkas buildings: The upper storeys are carried by the stone-masonry ground floor but in case of collapse, a secondary load-carrying system of timber columns is activated. These timber columns are fixed to the ground or, more usually, are free standing, but not embedded in the walls.
- These two systems are initially interconnected.



(Touliatos, NTUA, 1995)



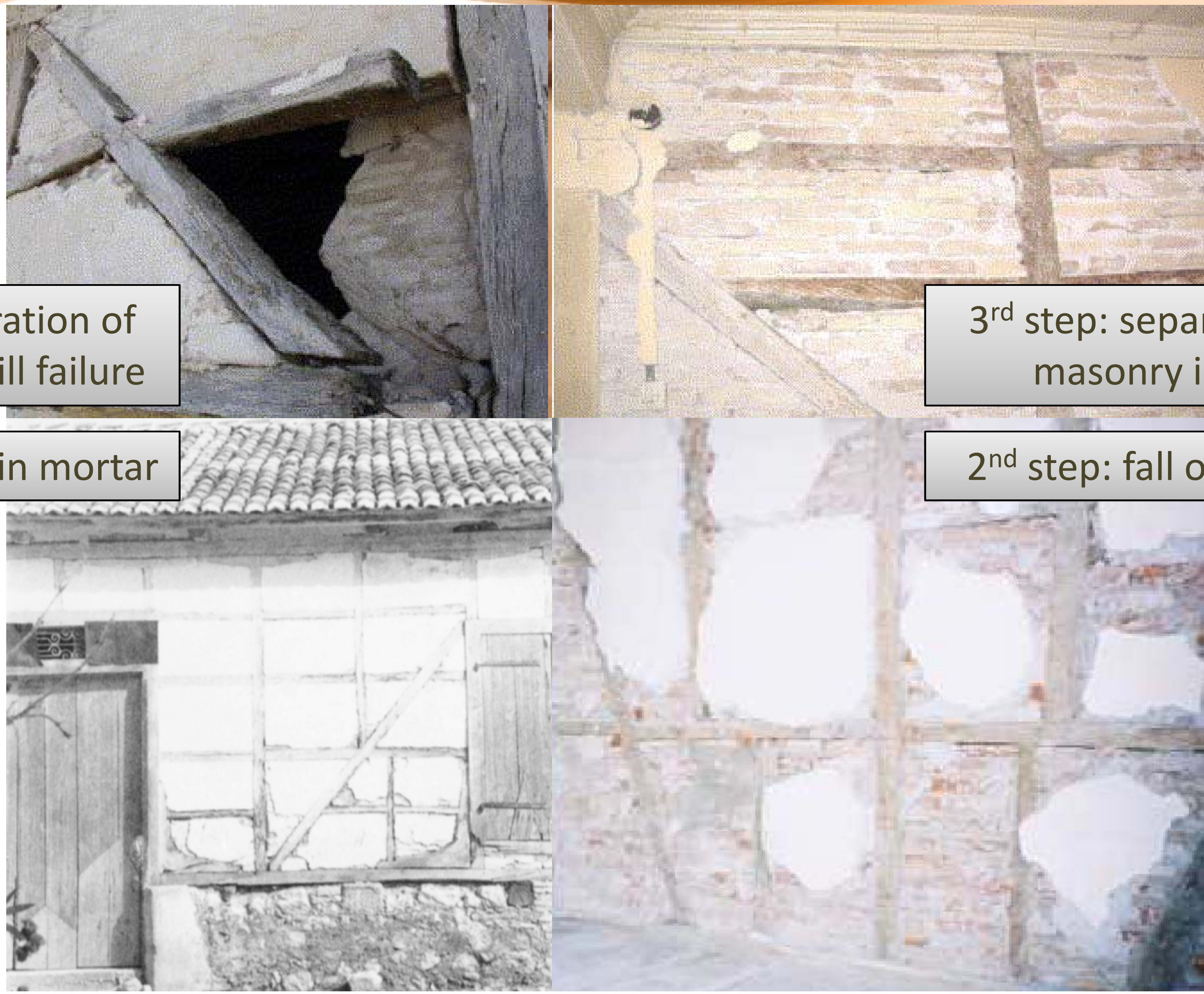
Timber framed construction in the course of history

Bronze Age | Ancient Greek and Greek-Roman Times | 16th – 19th | **Modern times**

- Nowadays, many heritage buildings of timber-framed masonry stand in Lefkas (GR), Lisbon (PT), Calabria (IT) and other cities.
- These buildings are used as dwellings, and many of them are exposed to high seismic risk.




Seismic behaviour of timber-framed walls



4th step: separation of diagonals – infill failure

3rd step: separation of masonry infills

1st step: cracks in mortar

2nd step: fall of mortar

Performance of timber framed structures in recent earthquakes

- Lefkas earthquake, 2002, M=6.4, epicenter near the city:
  - 34% of buildings were timber-framed
  - although the earthquake was strong (a_{max}= 0.42g , many R/C buildings damaged, one collapsed), damage to T-F buildings was limited to out-of-plane fall of external mortar, or, rarely, of masonry infills
- In Turkey, during the strong Düzce (1999) earthquake the behaviour of T-F buildings was good (better than old R/C), the opposite occurred during the lower magnitude Orta (2000) earthquake (reasons?..).

Performance of timber framed structures in recent earthquakes

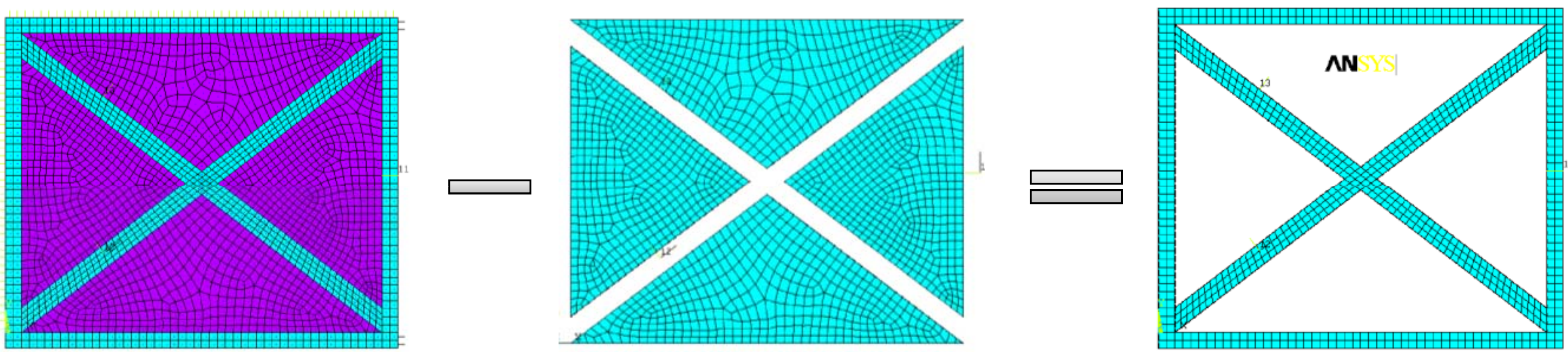
As a rule:

- observed performance of T-F masonry buildings is rather good, for high seismic intensities ↔ ability to dissipate earthquake energy efficiently through contact and friction
- performance during low intensity earthquakes not particularly good, due to early cracking of the masonry infills
- overall, T-F masonry seismic response is markedly non-linear.



Modelling of timber framed walls

- Masonry infills affect the performance of the walls primarily during the initial phase of elastic response.
- In a model focusing on the inelastic response, masonry infills can be indirectly taken into account.
- The result in the model is lower elastic stiffness, but better capturing of the overall response.

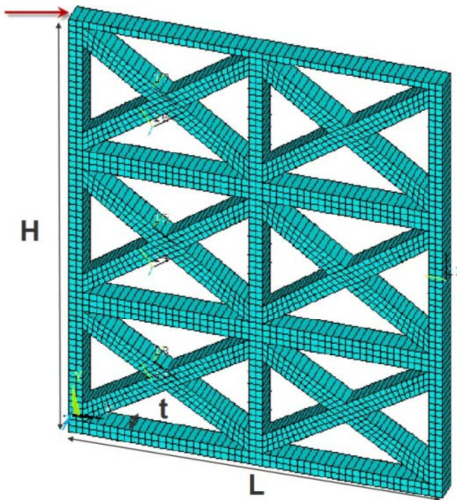


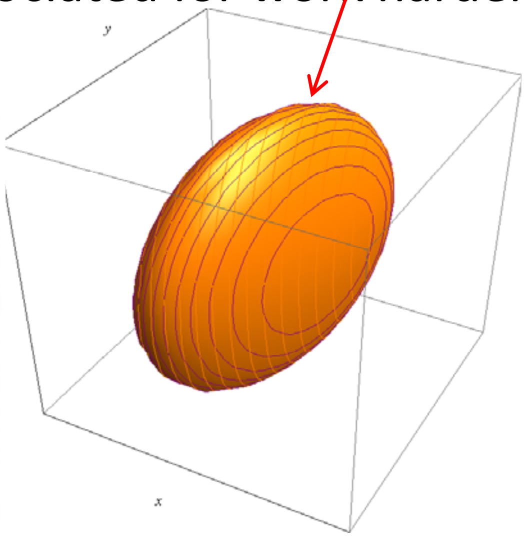
Modelling of timber framed walls

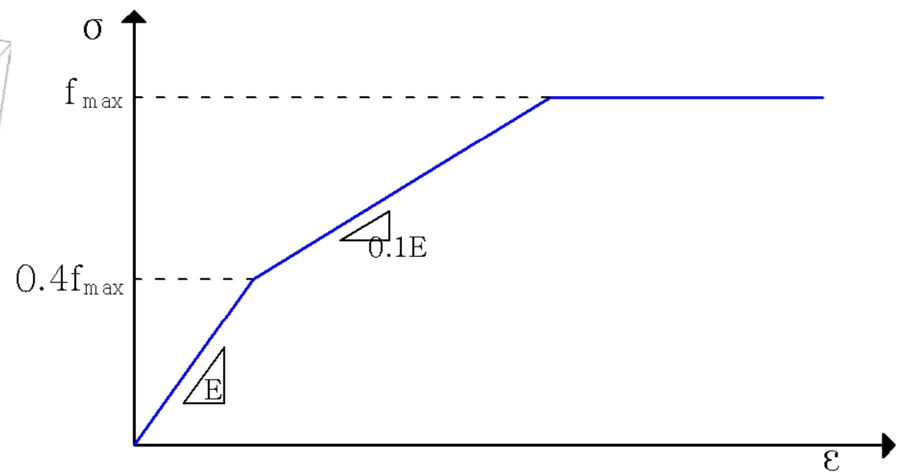
- Wooden members are modelled with area (2D) elements.
- The adopted yield law (and plastic potential function) for timber is the orthotropic Hill law.

$$\frac{1}{a^2}x^2+\frac{1}{b^2}y^2-\left(\frac{1}{a^2}+\frac{1}{b^2}\right)xy+\frac{1}{c^2}z^2=1$$

- The material law for monotonic and uniaxial stress is considered trilinear (for ±σ). Initiation of plastic deformation: at 40% of the final strength.
- Flow rule: associated for work hardening (isotropic).

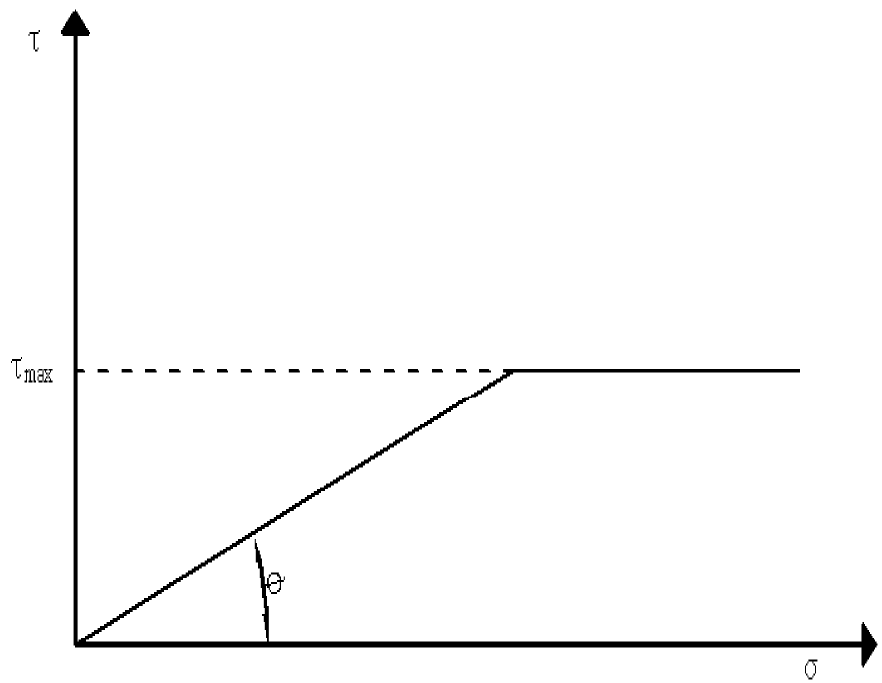






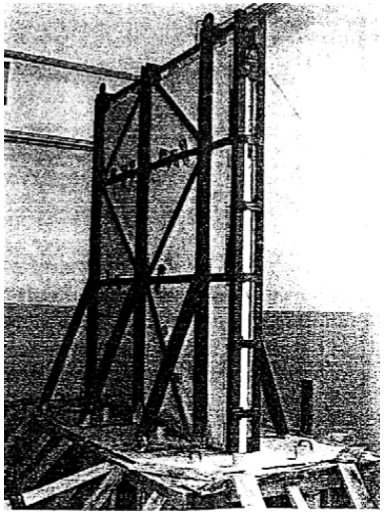
Modelling of timber framed walls

- Unreliable connection between timber elements → it is assumed that there is simple contact without any connection.
- Interface model for timber braces and posts: Mohr-Coulomb friction model (friction coefficient ≈ 0.5), without cohesion (c ≈ 0).
- For surface-to-surface contact asymmetric contact is assumed.
- Influence of masonry infills: (i)weight is taken into account indirectly, (ii) assumed to prevent buckling of diagonals.



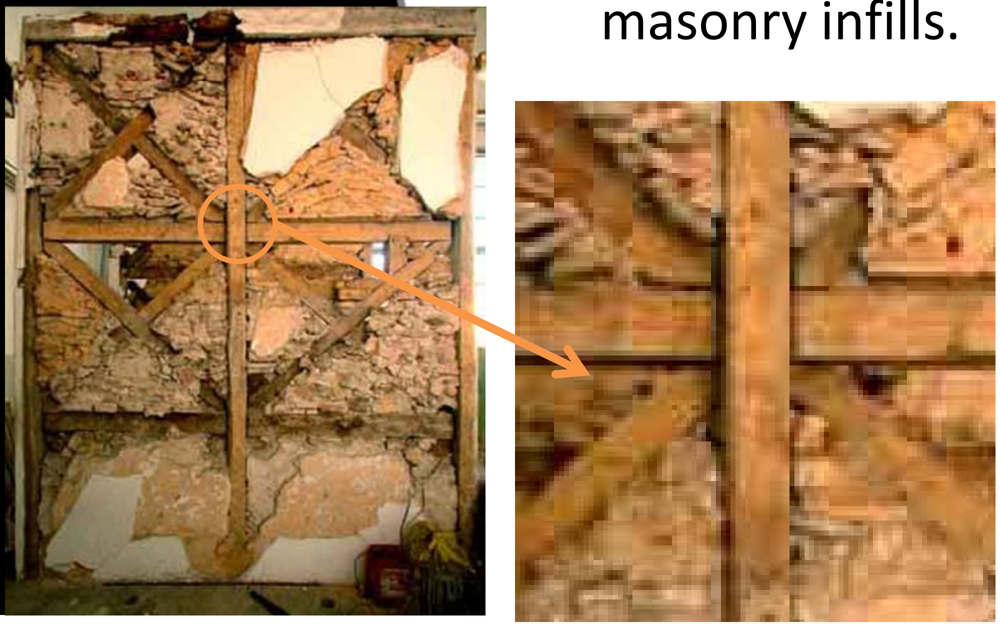
Validation of the model

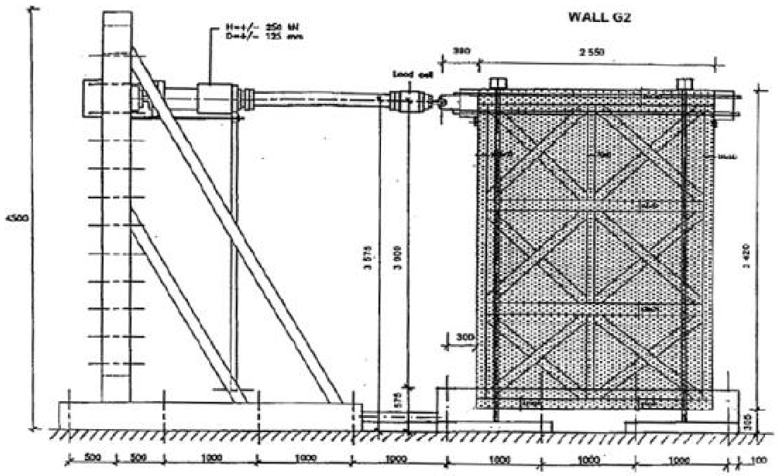
- The proposed model is validated against the results of laboratory tests performed at LNEC, Lisbon, by Santos (1997).
- In the laboratory tests three specimens were taken by an existing building of Lisbon.
- These specimens had large dimensions, with about 3.5m height (storey height), about 2.5m width and about 0.15m thickness.



Validation of the model

- The experimental testing consisted in the application of a reversed horizontal force until failure of the specimens.
- The behaviour of the three specimens was similar; at the final stage of failure they showed
  - unailing of the wooden braces
  - consequent sliding and partial expulsion of masonry infills.

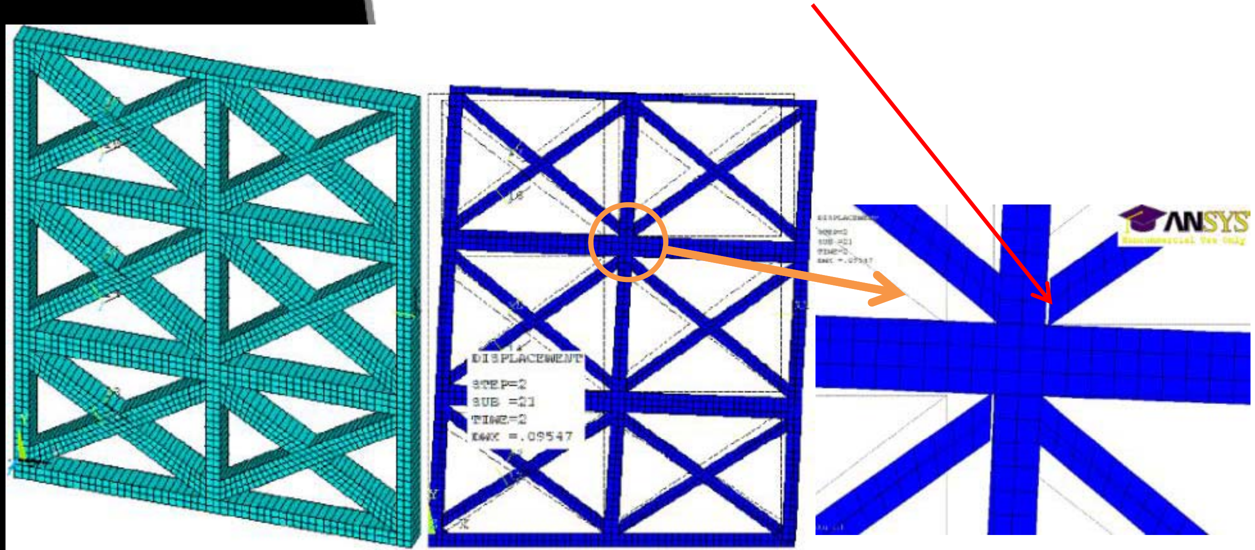




(Santos, LNEC, 1997)

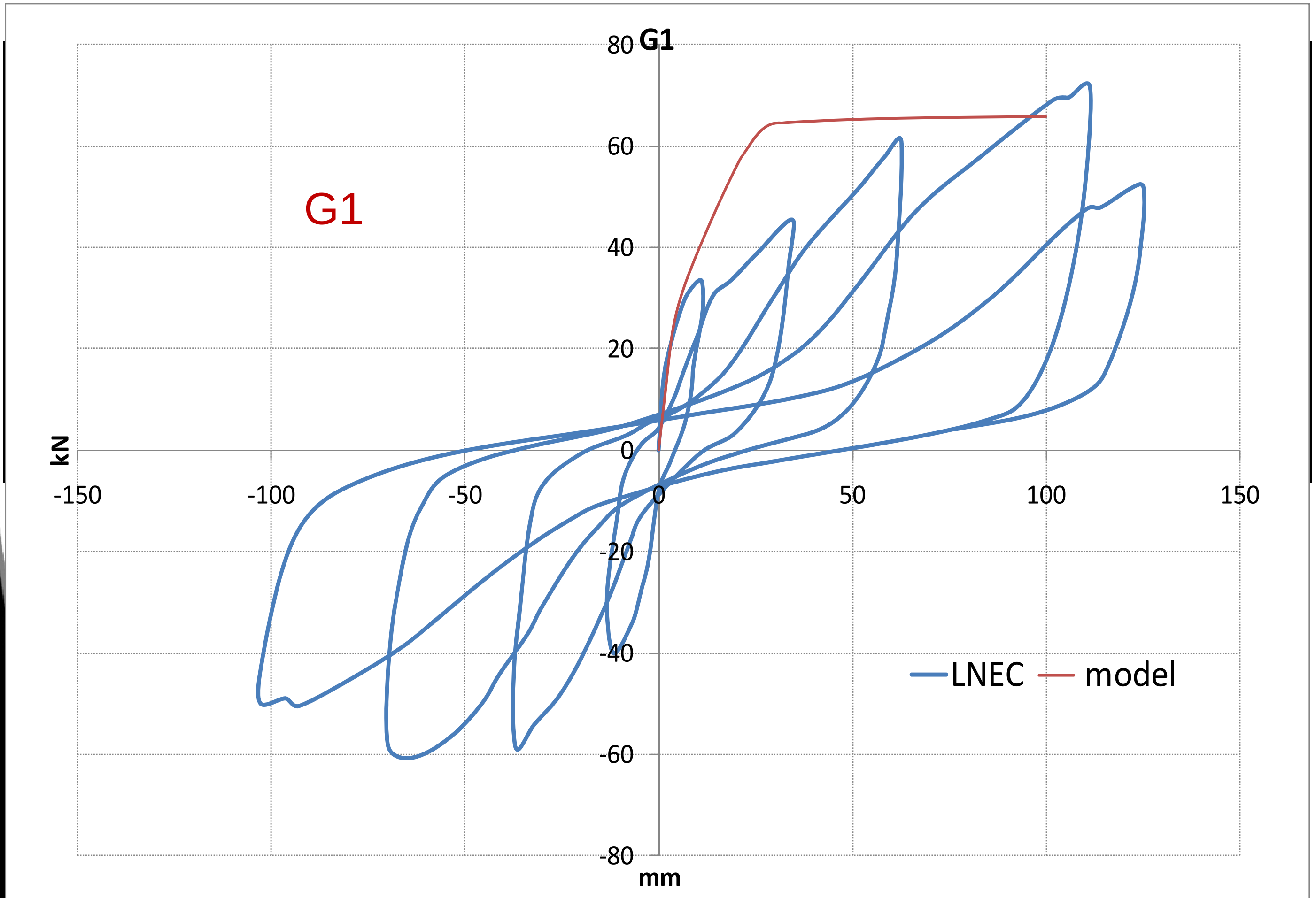
Validation of the model

- LNEC specimens were modelled in ANSYS using the proposed method (plasticity model)
- were subjected to monotonically increasing horizontal loading (with displacement control).
- The final deformed stage presents damage similar to that observed in the test specimens: disengagement of the diagonals from the surrounding timber members



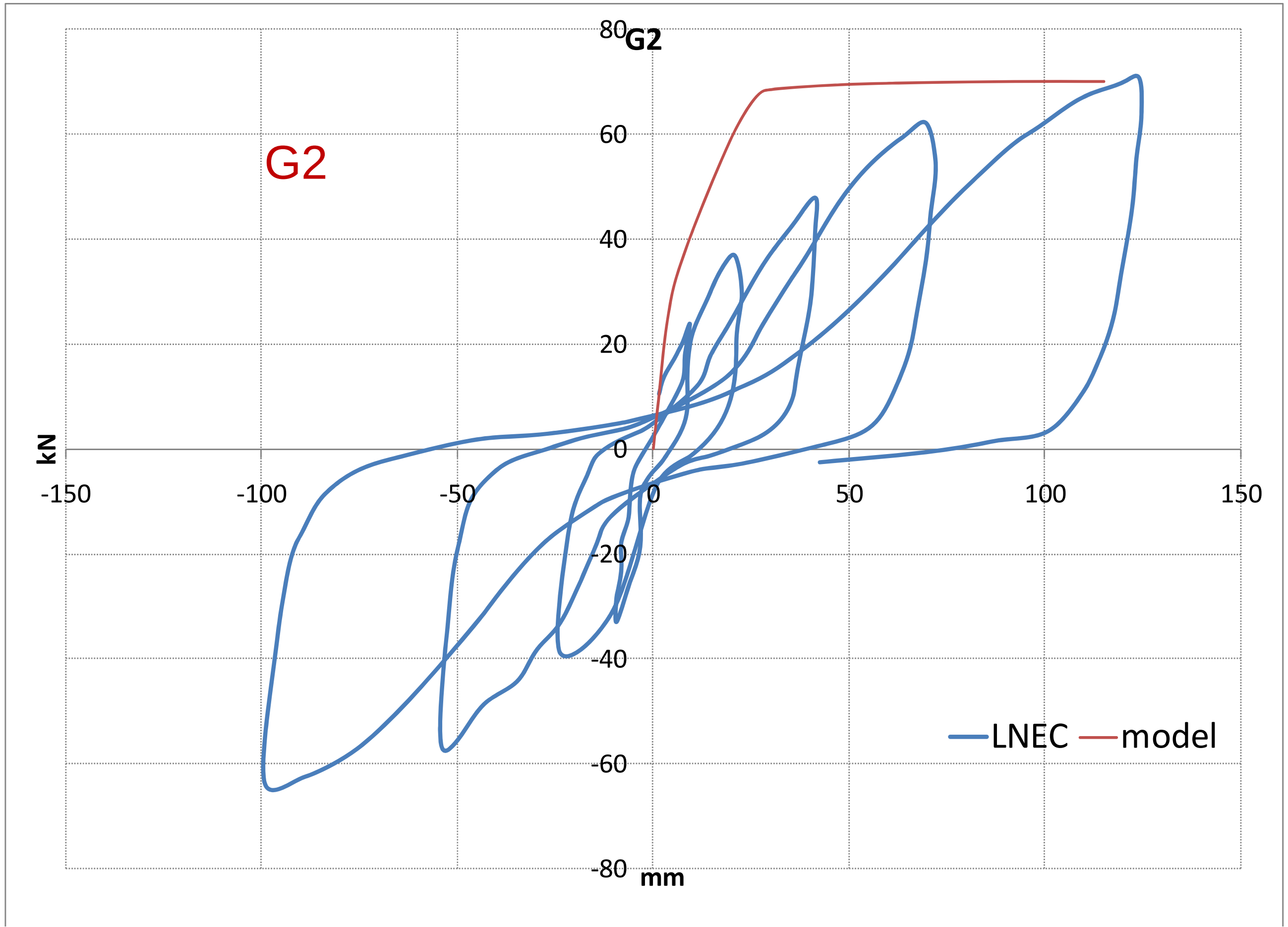
Validation of the model

- Analytical pushover curves are compared with the hysteresis loops from the tests,
  - good agreement is found



Validation of the model

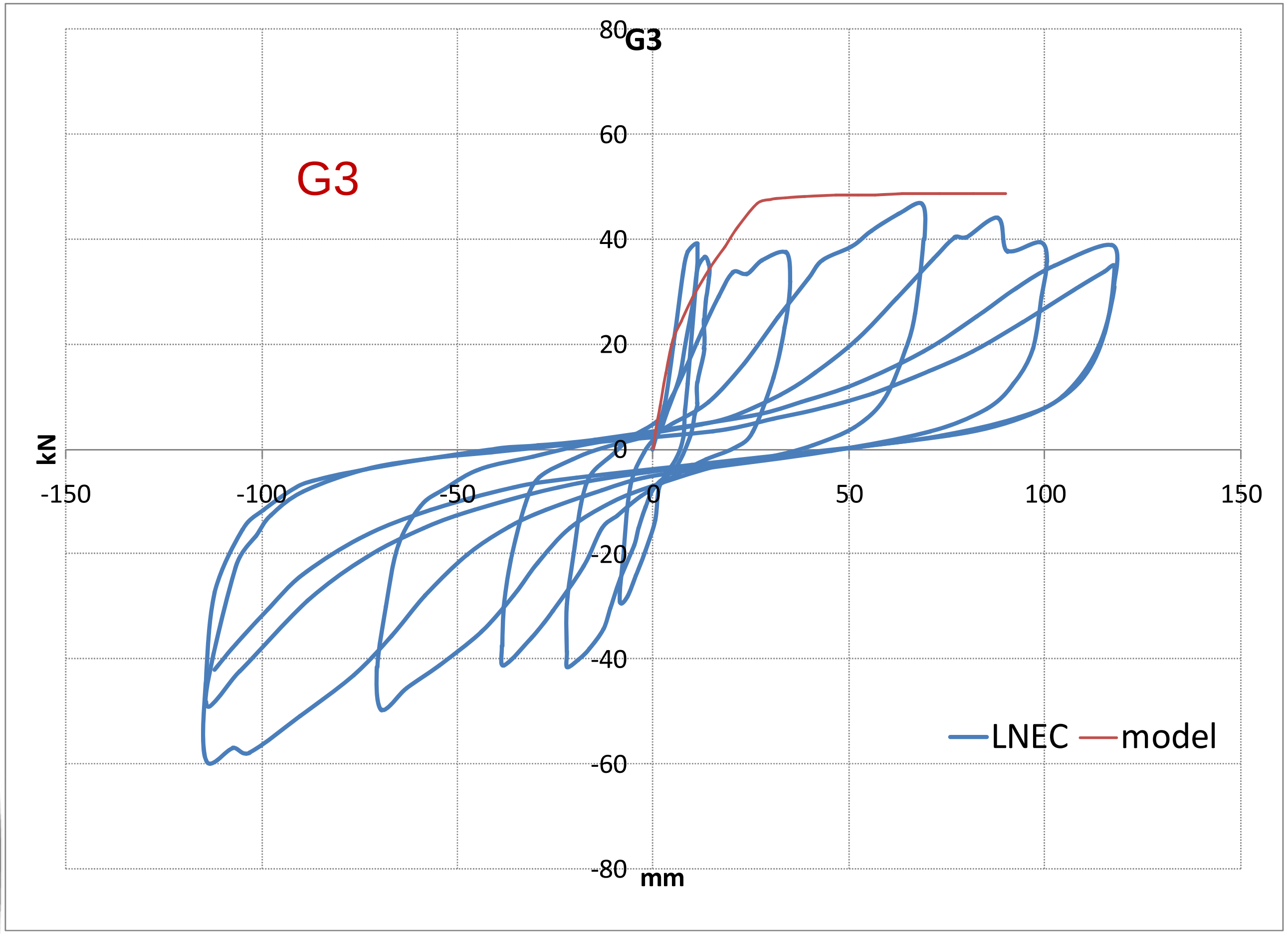
- Difference in the ultimate load capacity: 4%
- Difference in the ultimate deformation: 2.5%
- Difference in elastic stiffness: 5%



Validation of the model

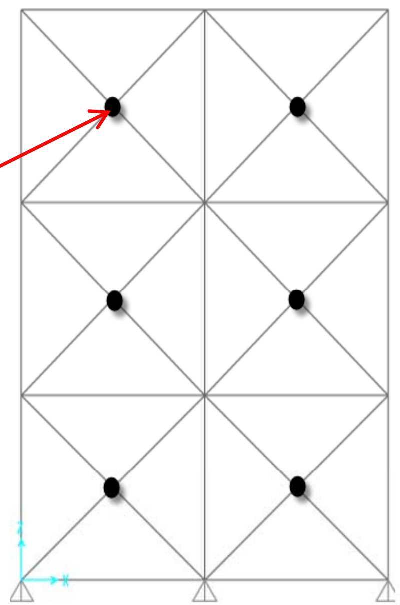
- Pre-peak range of the response: not captured properly in all specimens

  → local imperfections and wear of the timber



Simplified model for T-F walls

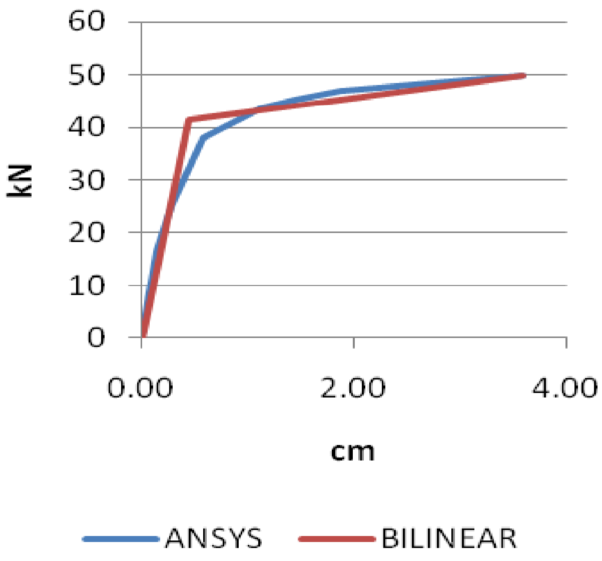
- Every timber post and lintel is modelled through a linear-elastic beam element.
- The diagonals are modelled with a link (bar) element pinned at its ends, hence carrying only axial compressive forces.
- A plastic axial spring is incorporated in these link diagonals.
- The inelastic constitutive law of this point plastic spring is then derived by means of the detailed model (bilinearization of the pushover curve).



$$u_{diag} = u_x \frac{\sqrt{H^2 + L^2}}{L}, \quad N_{diag} = V \frac{\sqrt{H^2 + L^2}}{L}$$

Simplified model of T-F walls

- Consideration of sliding of the diagonals in the elastic range is required $\rightarrow$ use results from refined model.
- The correction factor k_s is applied to the stiffnesses of the members of the beam model.



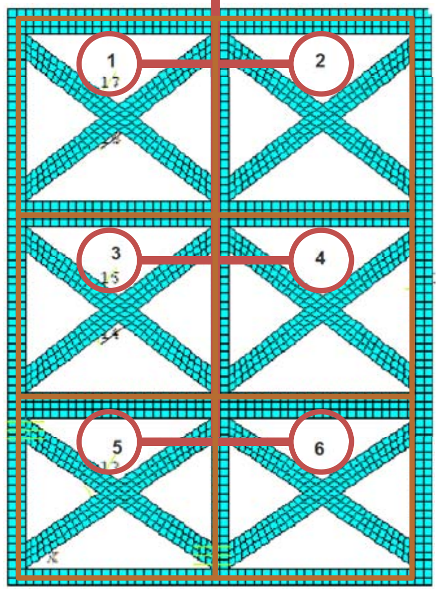
$$k_s = \frac{\left(H^2 + L^2\right)^{3/2} + H^3}{EA} \frac{1}{L^2} \frac{V_y}{u_y}$$

Initial stiffness of detailed model

Validation of the simplified model

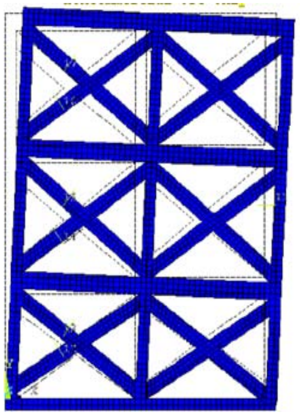
Model applied to LNEC specimens (six panels).

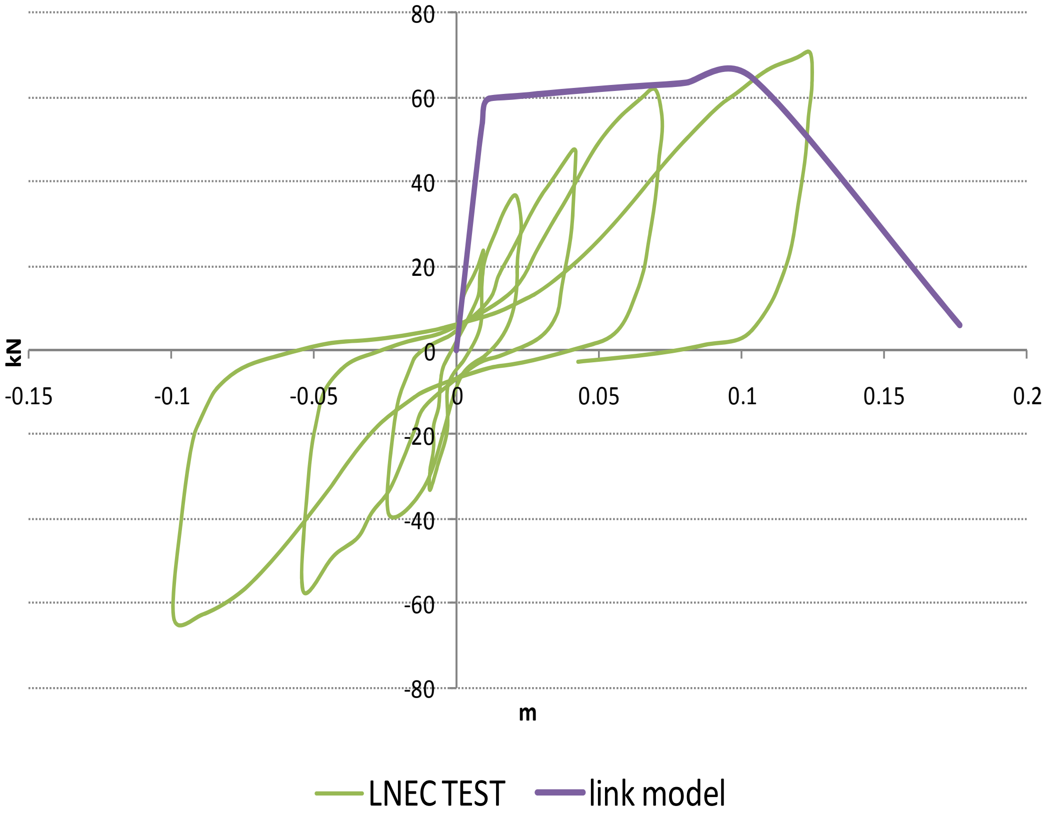
1. An elastic analysis is performed for the evaluation of the axial stress in each column.
2. The pushover curves derived from the detailed model are transformed into bilinear curves for the estimation of yield and maximum strain and strength.
3. These quantities are then expressed in terms of axial force and deformation.
4. The correction factor k_s is calculated for each panel.

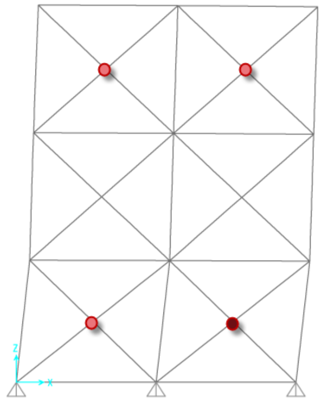


Validation of the simplified model

Specimen G2: Good match (as expected, since link model was calibrated against the refined model)





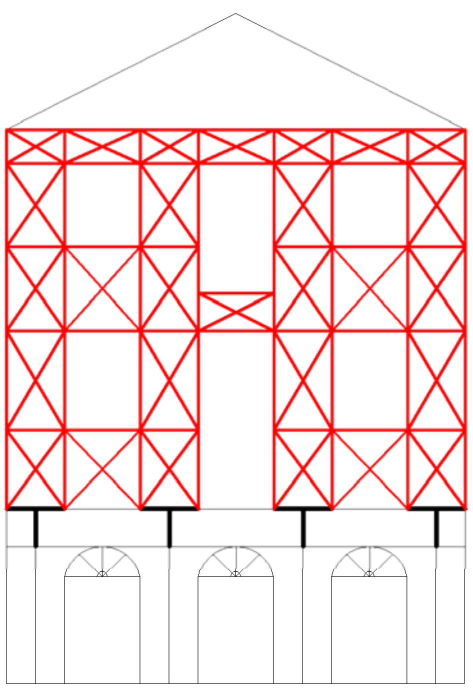


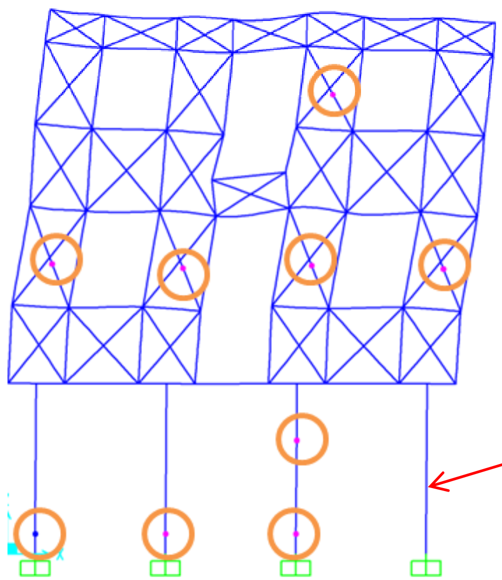
Application to an existing building

- The simplified model is used for the analysis of the façade of an actual building situated in the Ionian island of Lefkas, Greece.

- 'Berykiou' building:
  - basement in stone masonry of thickness 0.8m
  - two storeys built in T-F masonry
  - section of timber elements: 100mm square

Application to Lefkas building: results

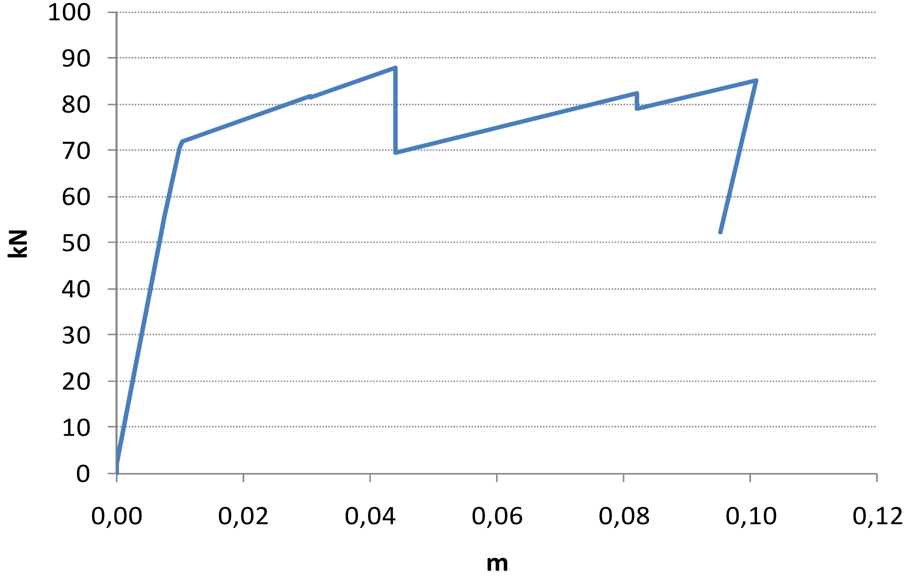




failure mechanism;
plastic hinges

Stone masonry piers

pushover curve



Conclusions

- From the Bronze Age to modern times we find timber-framed buildings of different configurations.
- The development of timber-framed structures is often closely linked to earthquakes.
- It might be hypothesized that, at least in earthquake-prone areas timber-framed construction was developed as a technique to effectively resist earthquake loading.
- Two models developed for the non-linear static analysis of T-F masonry buildings:
  - detailed (plasticity–based finite element)
  - simplified (beams – links)

Conclusions

- **Detailed model:** orthotropic behaviour for timber elements and a proper interface (Mohr-Coulomb), for their interaction ↔ **small subassemblages**.
- **Simplified model:** beam elements for timber posts and lintels, and link elements with nonlinear axial hinges for the diagonals ↔ **entire structures**.
- Masonry infill excluded from the model due to its insignificant contribution to seismic load resistance.
- The method was validated using the cyclic tests performed at LNEC.
- Good match found between results of numerical analysis and those of the tests.
- The detailed model can capture the gradual softening in the response of the walls.
- The pushover curve resulting from the simplified model has an essentially bilinear form.

Thank you for your attention!

Website: ajkap.weebly.com

Kouris, L. and Kappos, A.J. "Detailed and simplified non-linear models for timber-framed masonry structures", Jnl of Cultural Heritage, doi:10.1016/j.culher.2011.05.009, July 2011.