FIFTH INTERNATIONAL ITASCA SYMPOSIUM 2020 VIENNA, AUSTRIA

Dynamic analysis of masonry structures with DEM

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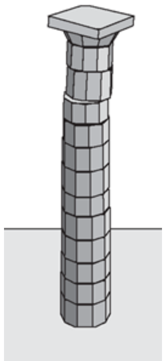
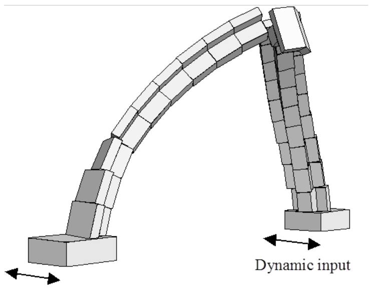
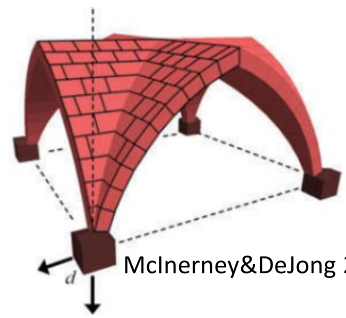
Dynamic analysis of masonry structures with DEM - Outline

- DEM for masonry
    - Range of problems
- Modelling options
    - Static and dynamic analysis
    - Rigid vs. deformable blocks
    - Block and joint models
    - Eigenvalue solution
    - Model calibration
    - Modelling large, complex, irregular structures
- Dynamics of rocking blocks
- Comparisons with shaking table experiments

DEM models for masonry structures - A wide range of applications





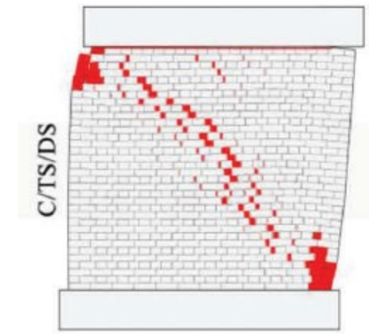


McInerney&DeJong 2015

Historical stone block masonry structures

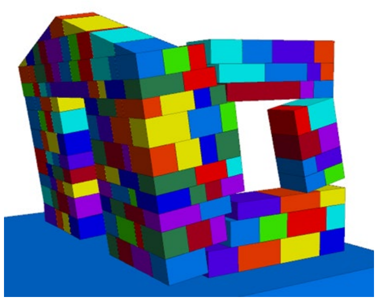
De Felice 2011

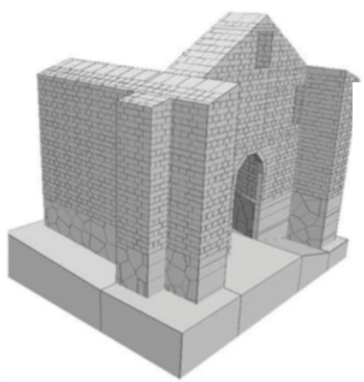
Traditional masonry



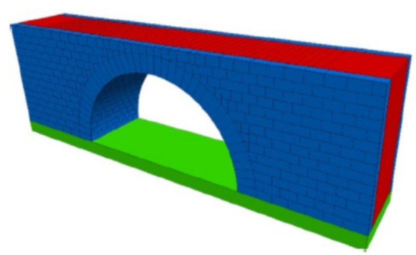
Malomo et al. 2019

Modern brick masonry walls / panels



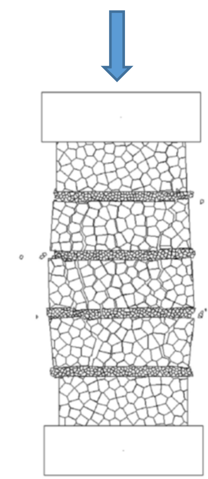


Mendes et al. 2018



Pulatsu et al. 2018

Large / complex structures

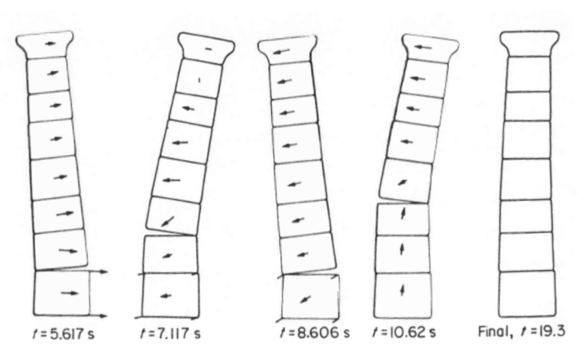


Detailed micro-models

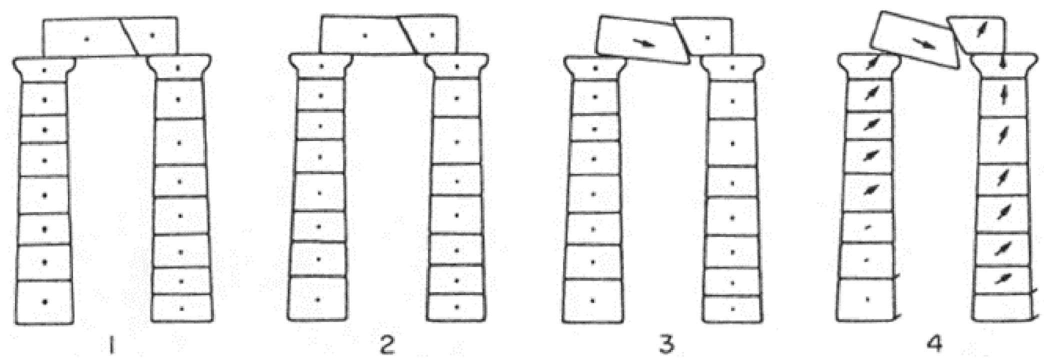
Sarhosis&Lemos 2018

Early DEM models for masonry dynamics

- In the early ‘90s, Peter Cundall and Loren Lorig applied UDEC to the analysis of classical columns, in collaboration with Dimitri Papastamatiou and Ioannis Psycharis, from NTU Athens
- Rigid block models of drum columns of the Temple of Apollo (Bassae) under seismic loading were developed



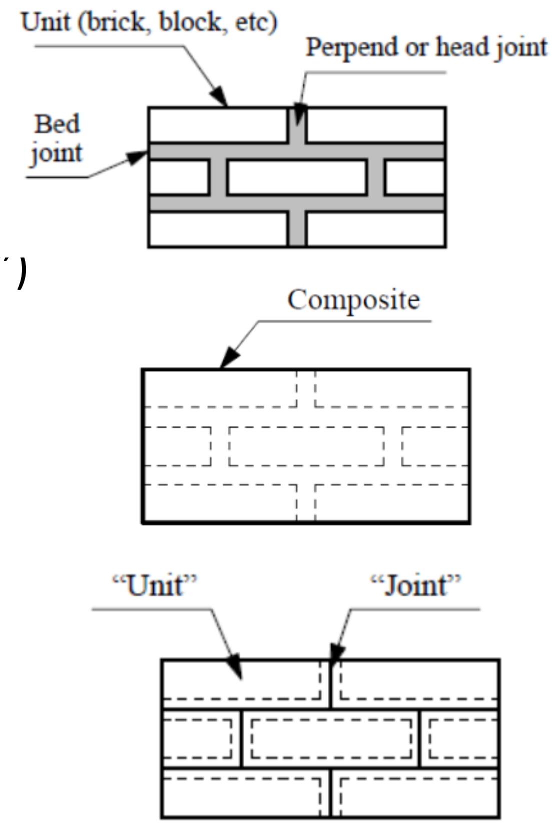
Single column rocking



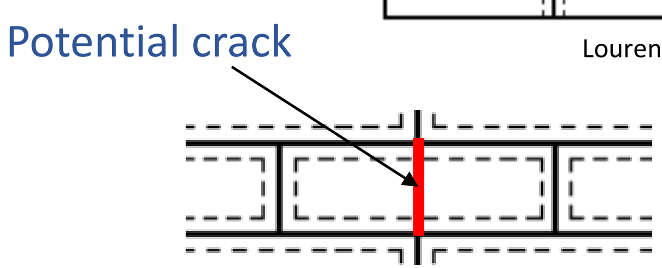
Architrave collapse

Masonry modelling

- As in rock mechanics, there are 2 approaches to model masonry:
  - Equivalent continuum (usually named “macro-models”)
  - Discontinuum (“micro-models”)
- Joints may be dry or mortared; mortar may be
  - Represented by the joint constitutive model, defining stiffness and strength parameters
  - Explicitly discretized in detailed models
- Block constitutive models
  - Rigid or elastic in most cases
  - Block fracture: insert discontinuity with tension/cohesion
- Joint constitutive models
  - Mohr-Coulomb most widely used
  - Softening models for mortar joints available



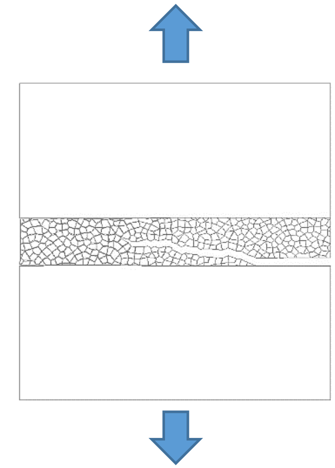
Lourenço 1996



Scale of DEM analysis

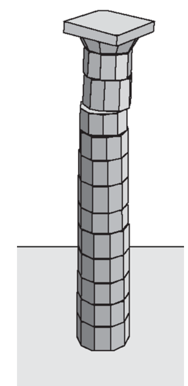
- <u>Detailed models</u> (“meso-scale”)
    - Bonded block models (e.g. Voronoi patterns, ...)

  > fundamental studies, lab tests, fracture propagation, ...



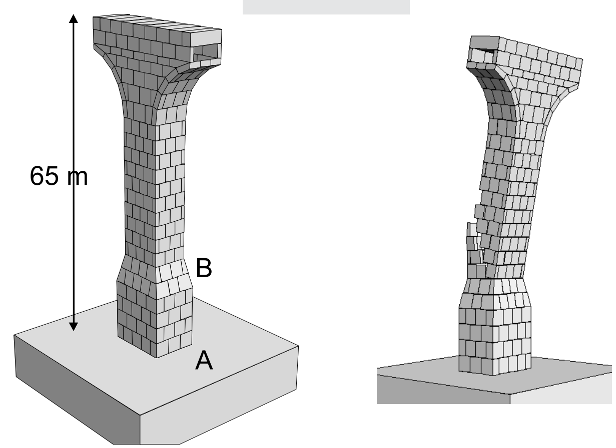
- <u>One-to-one block representation</u>
    - Model reproduces real block dimensions

  > simple masonry structures/components



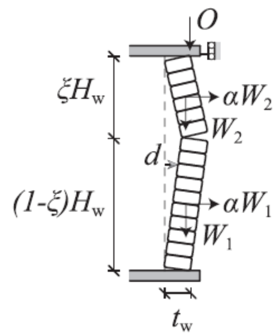
- <u>Simplified block system</u>
    - Numerical blocks larger than real blocks (represent a group of physical blocks)
    - Simplified joint patterns

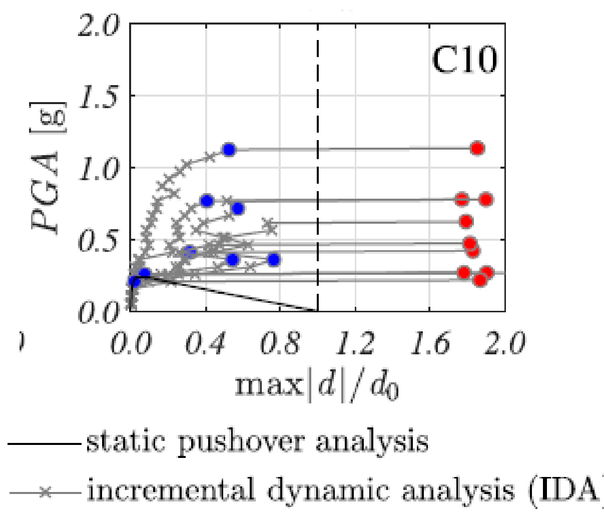
  > most complex structures



Modelling seismic loading

- Static analysis (pushover)
  - Out of plane failure of panels, Godio&Beyer (2018):
    - Experiments and UDEC models
    - Comparison of pushover and dynamic analysis

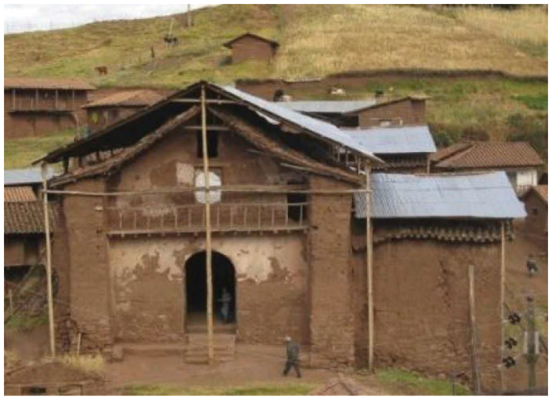


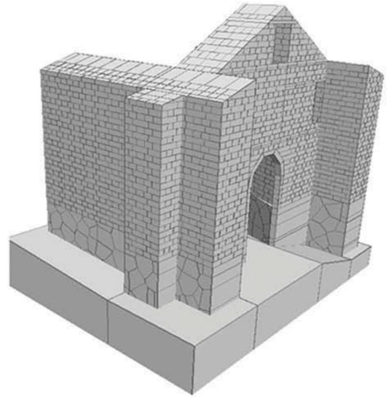


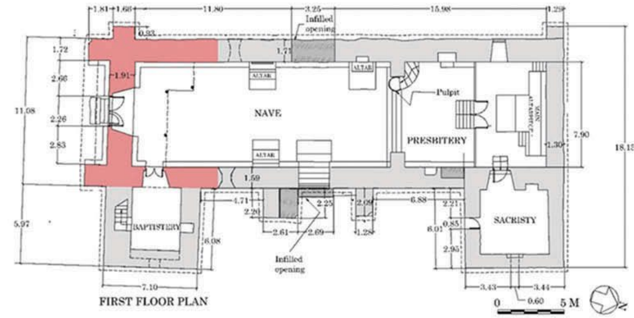
- Dynamic analysis
  - Time domain explicit analysis with UDEC/3DEC:
    - Natural frequencies of structure have to be represented
      - For historical structures, in situ measurements are recommended
    - Run times are usually large due to small time steps
      - Simplifications of model are essential (no. of blocks, details, ...)
      - The stiffness-proportional component of Rayleigh damping may reduce too much the time step

Pushover analysis

3DEC model of adobe church – Kuno Tambo (Peru)

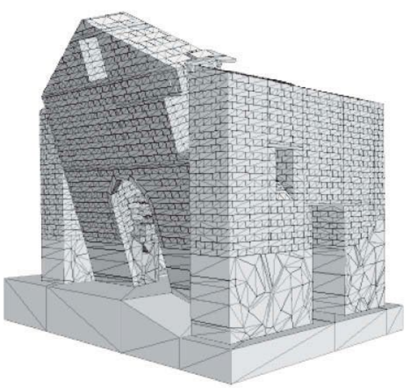




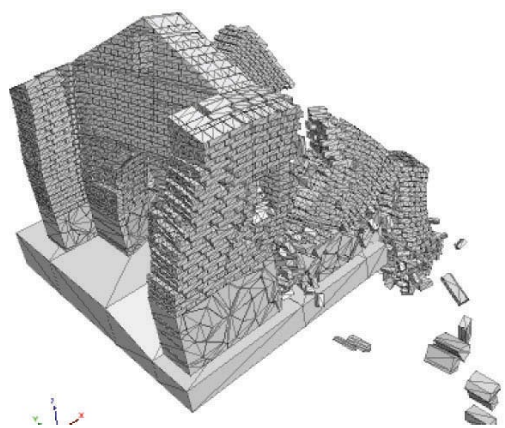


3dec model of the façade and adjacent walls

Failure modes obtained by static pushover analysis



Outwards failure of the façade (0.19g)



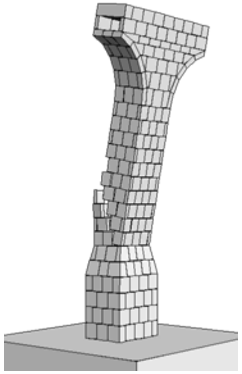
Inwards failure of the façade with colapse of side walls (0.37g)

Mendes et al (2018)

Rigid blocks vs. deformable blocks

- Rigid block models
  - All deformation concentrated at the joints
    - Kn, Ks joint stiffnesses represent global structural deformability (units and mortar)
    - For dynamic analysis of historical structures, in situ measurements of natural frequencies allow calibration of stiffnesses
  - Mostly useful for dynamic analysis, as they allows larger time steps in explicit codes

- Deformable block models
  - Blocks with internal triangular/tetrahedral zones; typically assumed elastic
  - Require definition of block E and joint Kn, Ks
    - In simplified block models, various options exist for distributing global deformability between joints and blocks



Eigenvalue analysis

- For **rigid block models**, 3DEC performs calculation of eigenfrequencies and eigenmodes
  - The kinematic variables are 6 degree-of-freedom per rigid block
  - A stiffness matrix is assembled using the contact stiffnesses

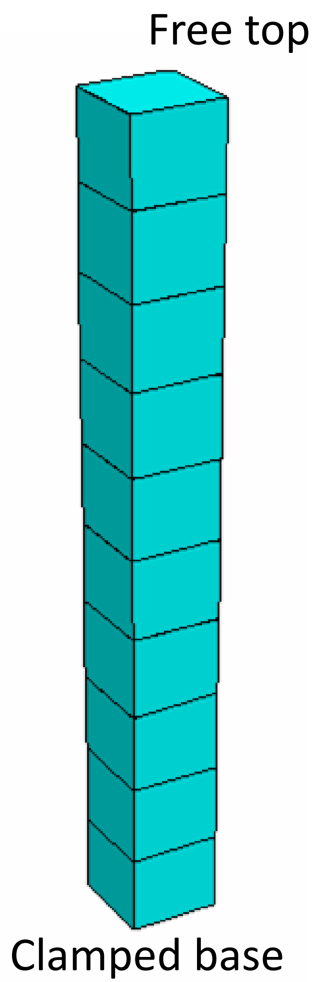
Square pillar – Eigenfrequencies of 3 beam bending modes

Mode	Euler-Bernoulli theory	Timoshenko beam theory	Model A continuum FE	Model B deformable blocks	Model C rigid blocks
1	1.02	1.02	1.02	0.96	0.92
2	6.40	6.09	6.03	5.61	5.61
3	17.9	16.1	15.7	14.4	15.0

Model A: 3dec Feblocks (20-node brick elements, no joints)

Model B: 20-node brick FE's + joints
50% of total deformation in the joints

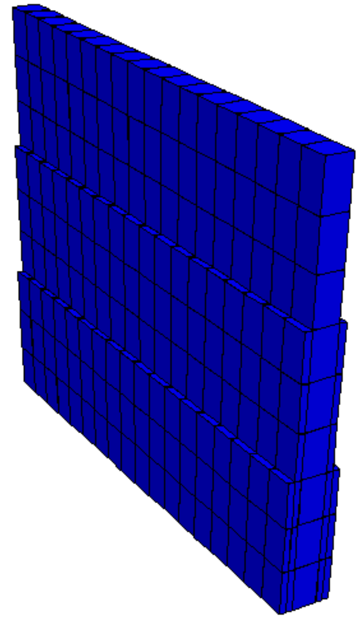
Model C: rigid blocks (3x3 contacts in cross-section)



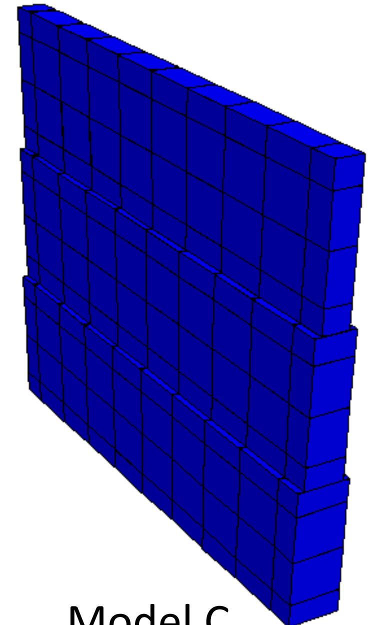
Stepped cantilever wall - Eigenfrequencies

Mode	Mindlin plate theory	Model A continuum Feblocks (3DEC)	Model C rigid blocks
1	1.40	1.40	1.36
2	2.52	2.50	2.99
3	5.46	5.37	5.48
4	6.18	6.10	6.68

analytical solution:
Liu & Buchanan 2004



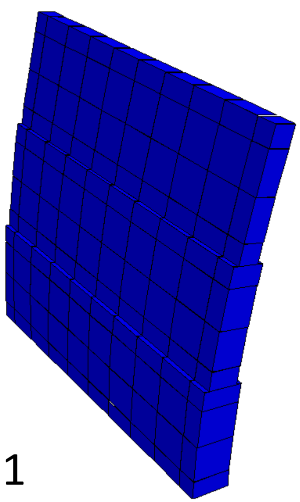
Model A – continuum
20-node brick elements



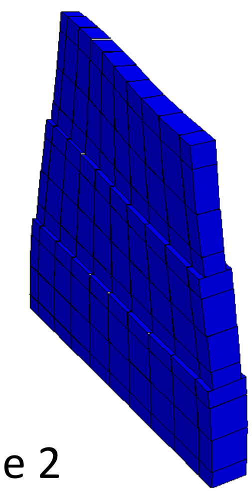
Model C
– rigid blocks

Time step for dynamic analysis:

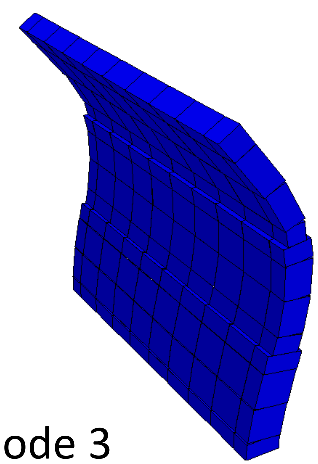
Model A: 3.5e-5 s Model C: 2.4e-4 s



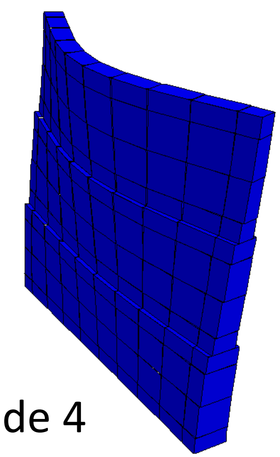
Mode 1



Mode 2



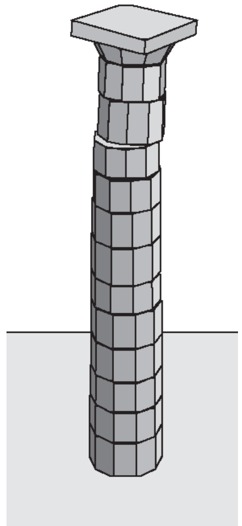
Mode 3



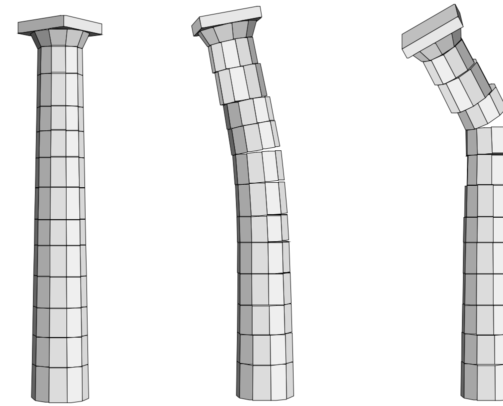
Mode 4

Seismic modelling of drum columns
The Parthenon project – NTU Athens

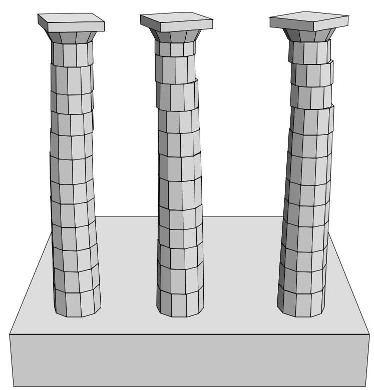
Shaking table test of marble
drum column, 1:3 scale
NTU Athens
Papantonopoulos et al. (2002)



3DEC models, using rigid
blocks, frictional joints



Single column - 3 stages of collapse

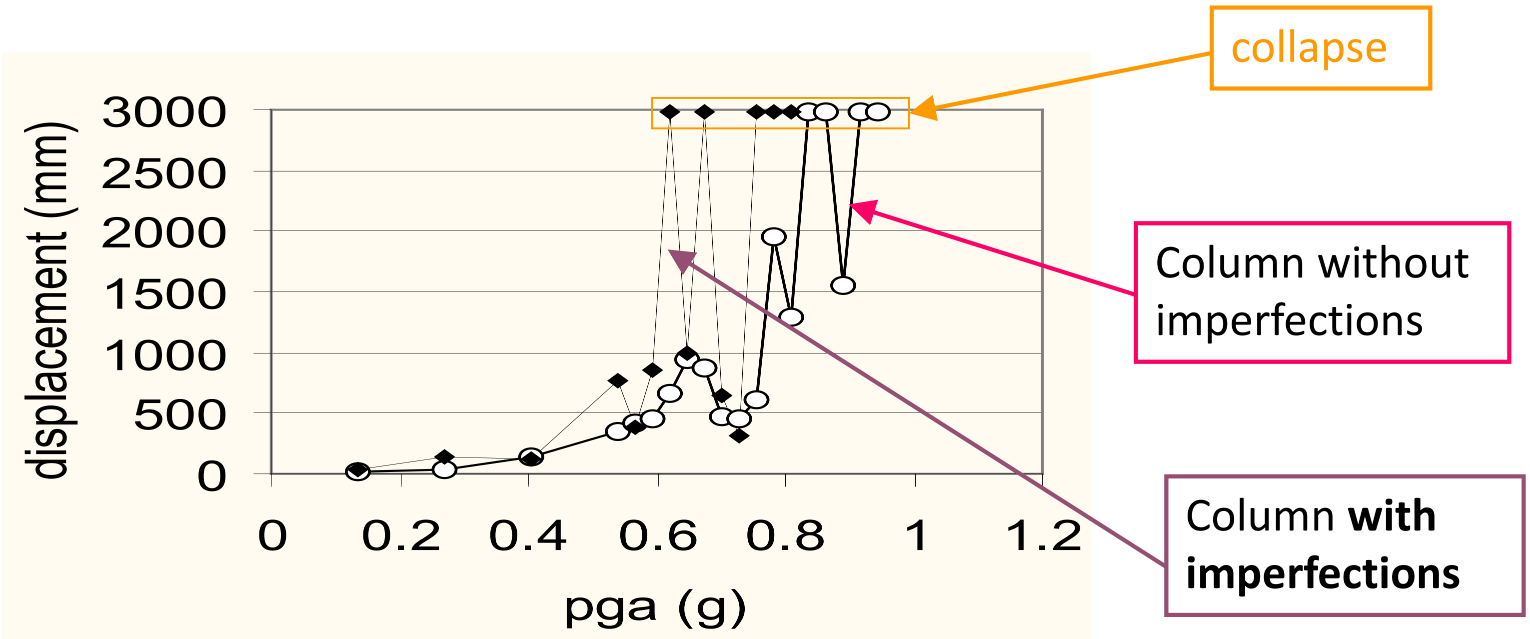


The variability of rocking dynamics

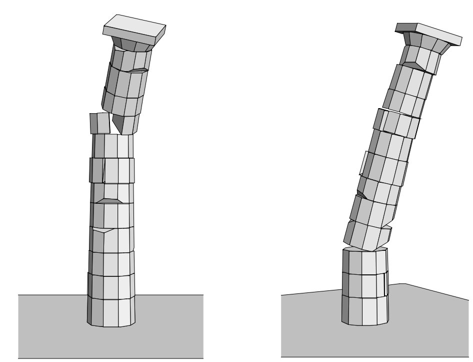
3 similar columns with
different drum heights
(under Kalamata record scaled to 0.7g)

Variability in rigid block dynamics

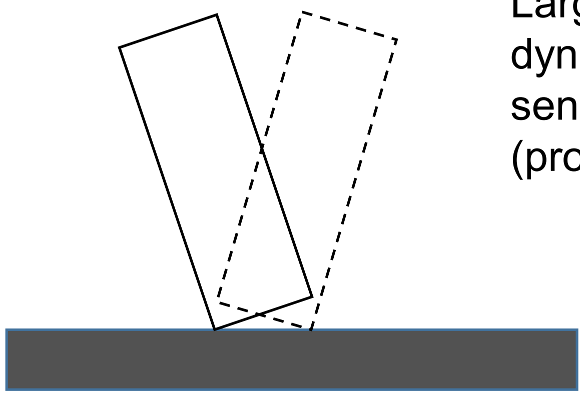
3DEC analysis of single drum column, subject to the scaled Kalamata record



Maximum permanent displacement vs. peak input acceleration



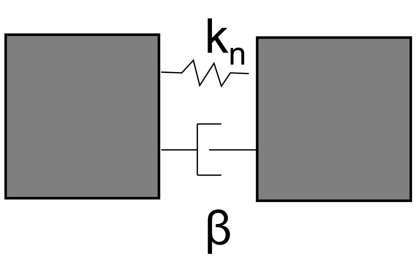
Dynamic block rocking and overturning



Large amplitude rocking is a non-linear dynamic problem, typically showing sensitivity to small variations in input data (properties, input motion)

- Housner classical analytical solution
  - restitution coefficients (energy dissipation on impact)

- DEM numerical solutions
  - Spring-dashpot contact models



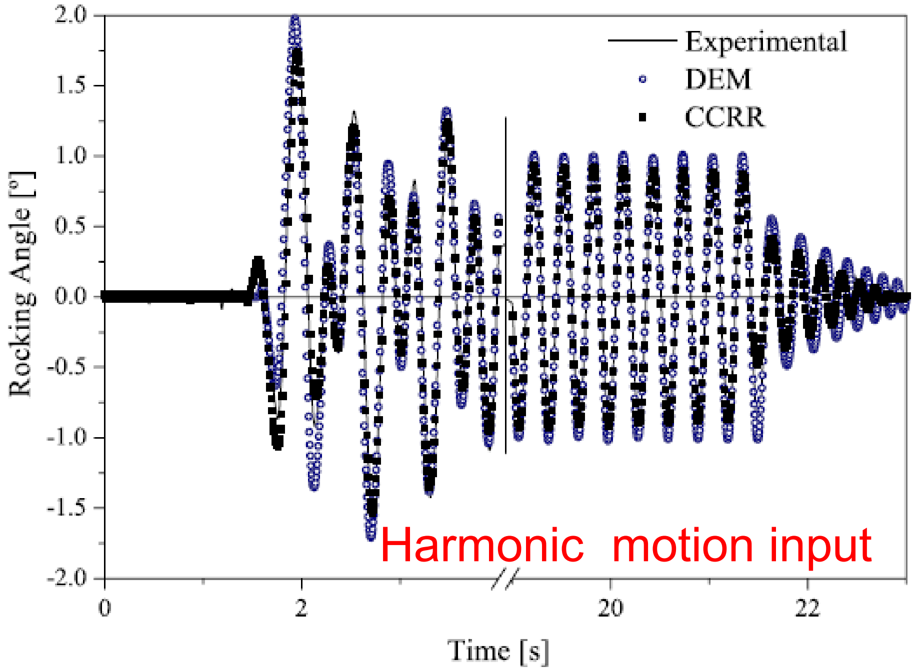
Granite blocks with different aspect ratios

Pena et al., 2007

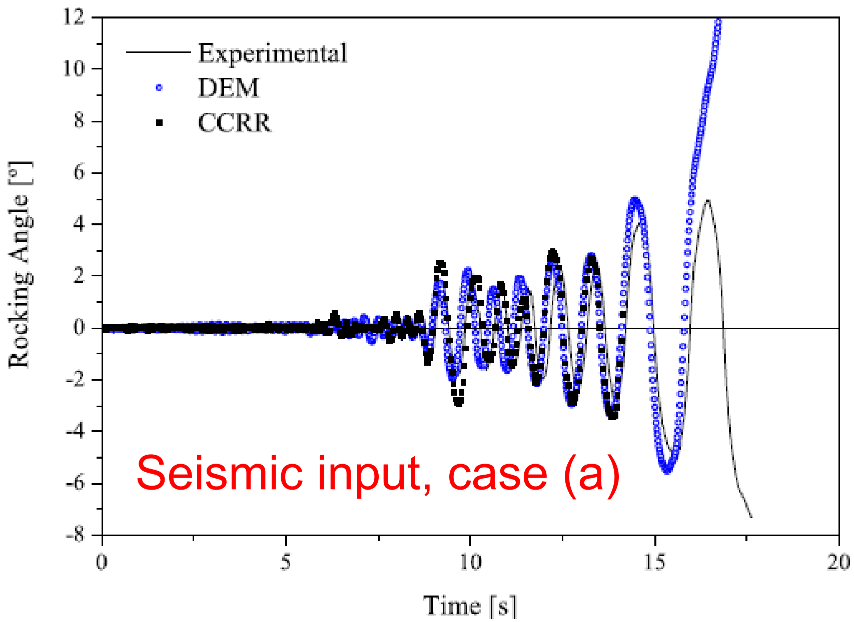
Tests at LNEC shaking table

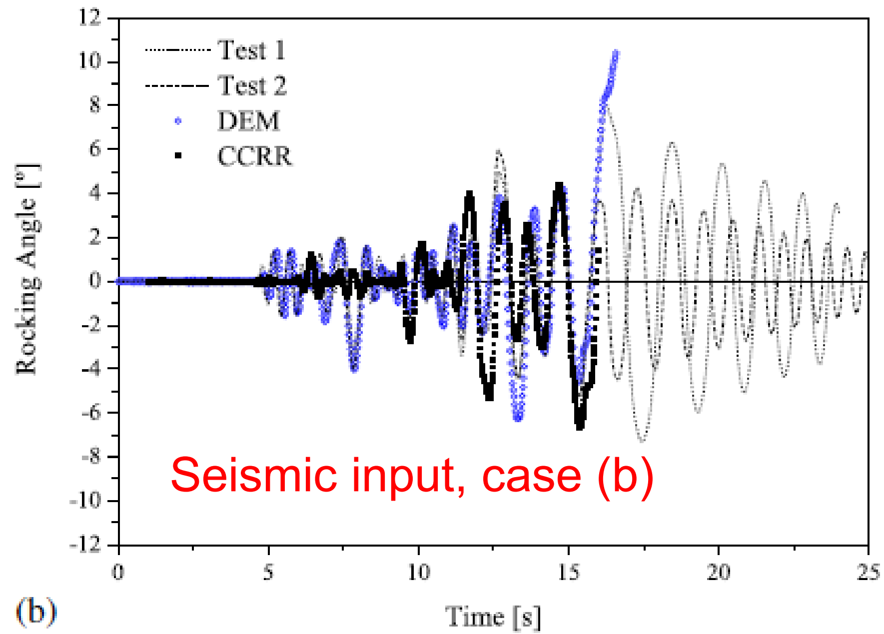
Single block rocking – experiments vs. DEM (UDEC)

Pena et al. 2007

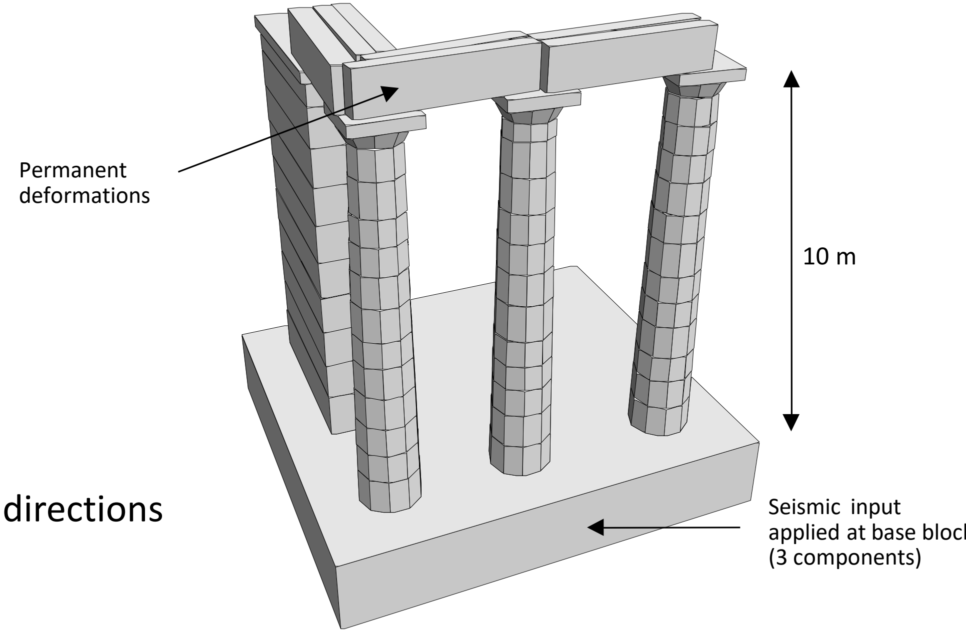


DEM – UDEC model
CCRR – analytical (F.Prieto)



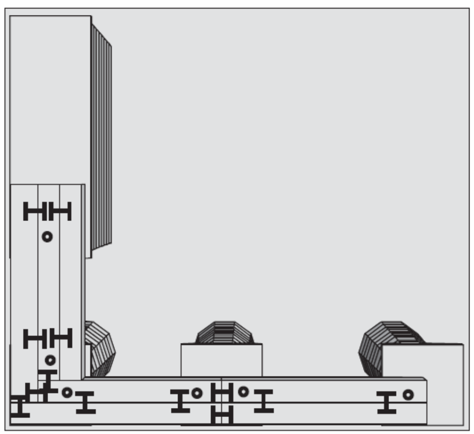


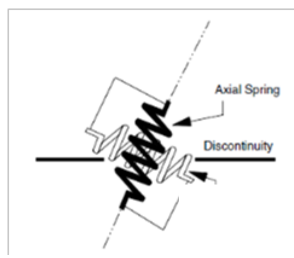
Seismic analysis of the restored Parthenon Pronaos



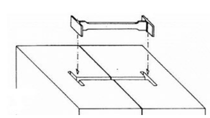
3DEC structural axial elements

- nonlinear (breakable) springs
- placed across joints in the normal and shear directions

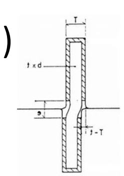




architrave-architrave clamps (**I**)



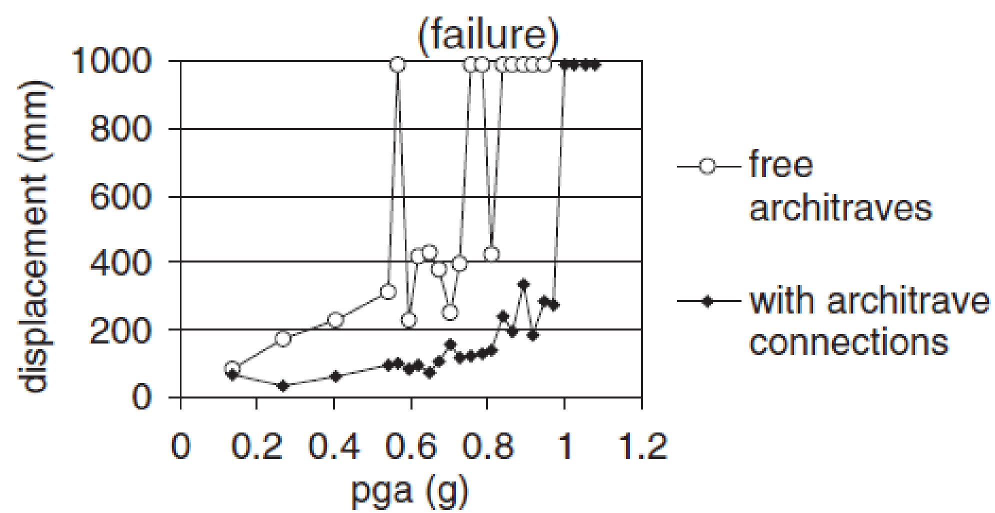
architrave-capital vertical shear dowels (◦)



Free architraves

Permanent deformations (max. disp. 0.17 m)

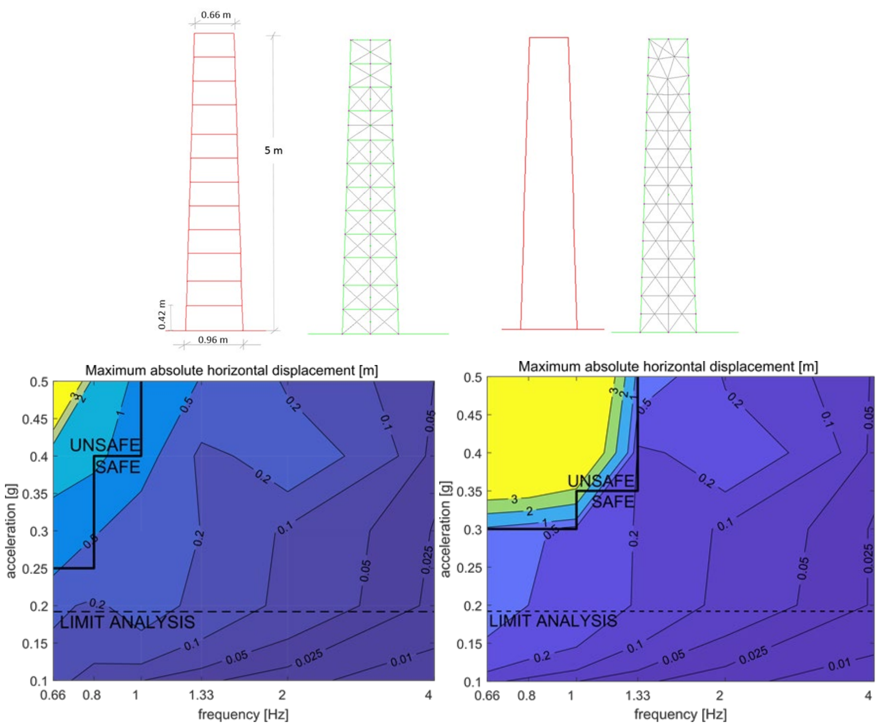
Kalamata record (0.27g)



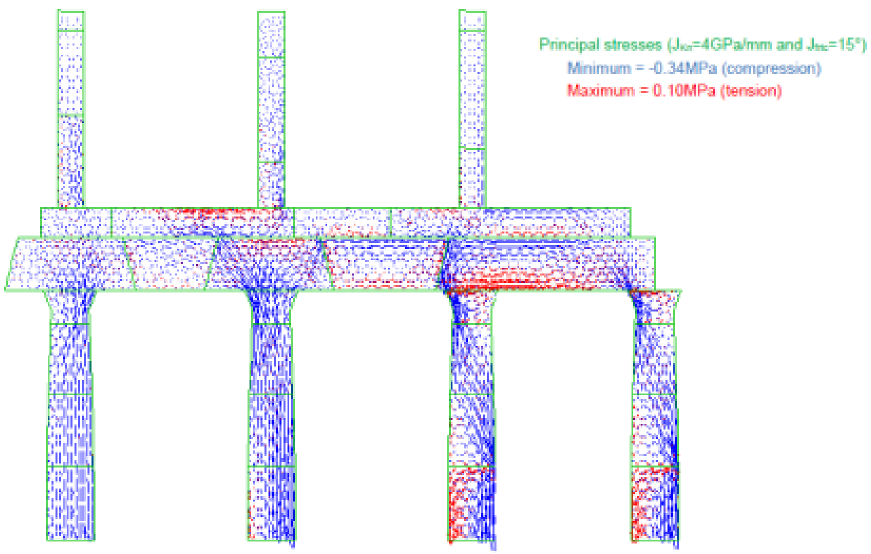
Psycharis et al. 2003

Deformable block models

- Deformable blocks models provide internal stresses and finer discretizations of contacts
- Run times may be acceptable in 2D dynamic analysis



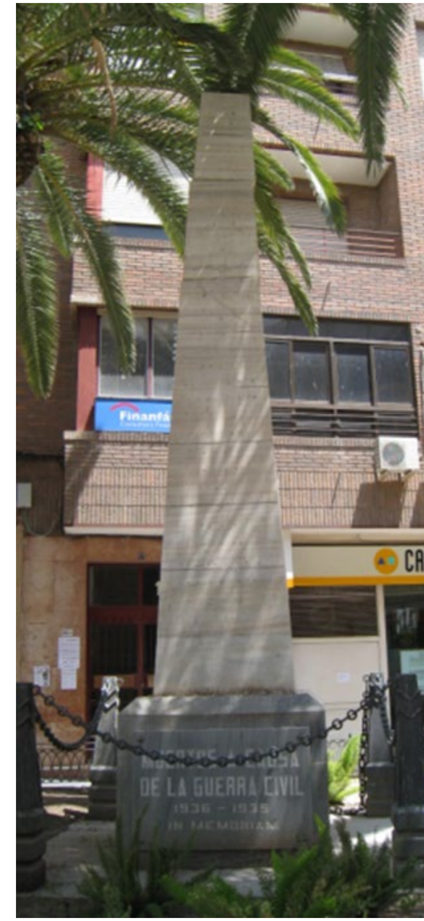
Sarhosis et al. 2019

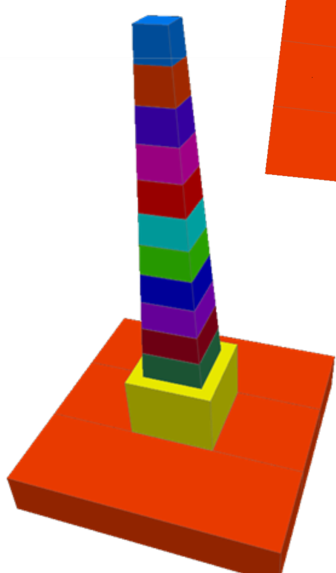


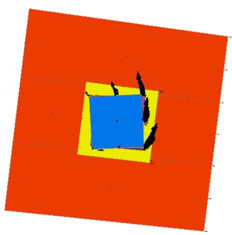
Sarhosis et al. 2015

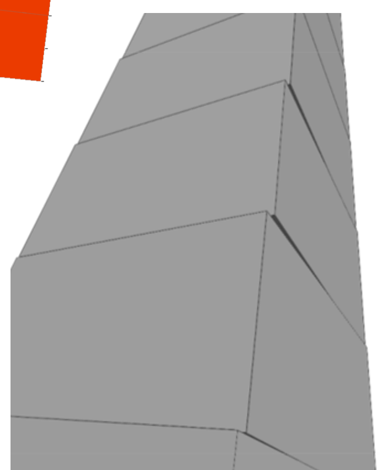
Permanent displacements in obelisk subject to the Lorca 2011 earthquake

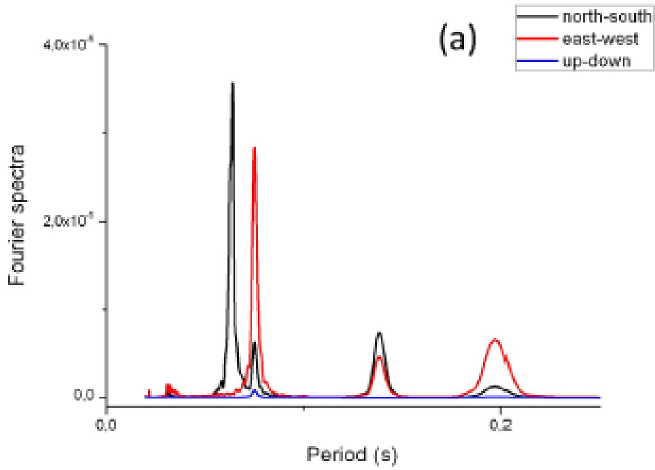
- 3dec rigid block model
- Joint stiffnesses (including foundation joint) calibrated to match measured natural frequencies
- Dynamic input: Lorca 11 May 2011 strong motion record (3 components, max = 0.36g)
- Model reproduced the observed rotational sliding in the earthquake





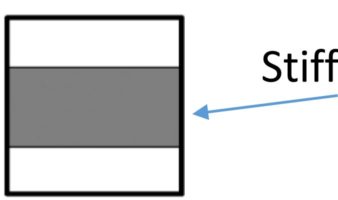






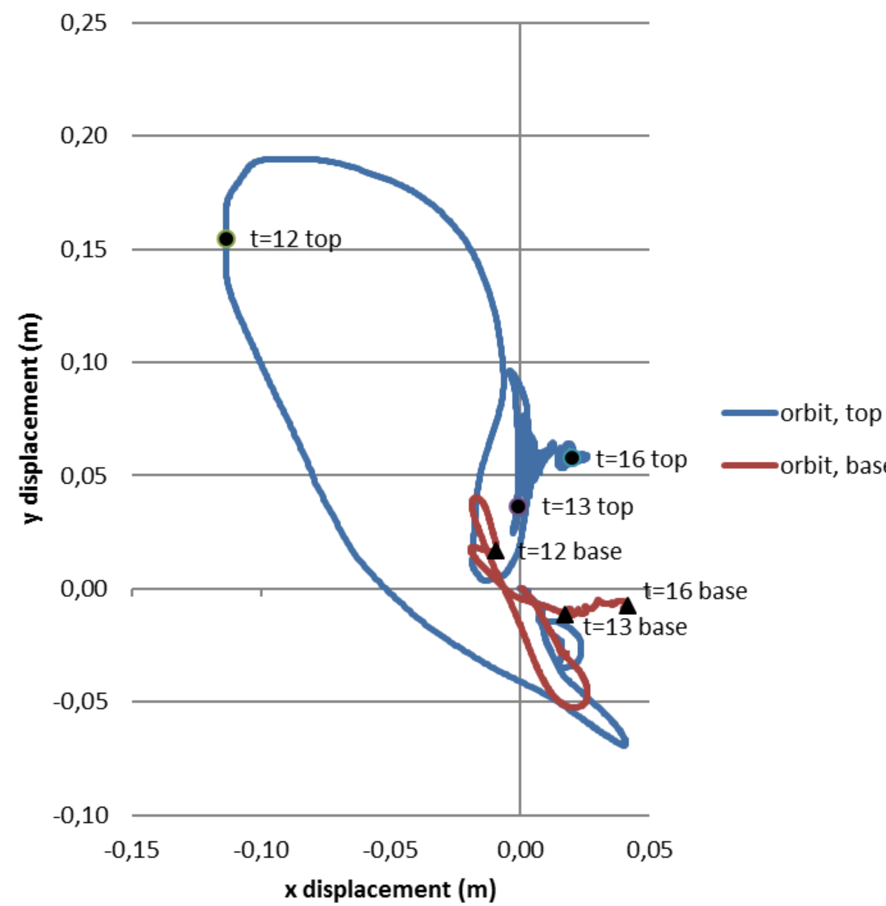
In situ measurements show different natural periods in NS and EW directions (0.06 and 0.08s)

The measured frequencies were reproduced in the model by means of a variable stiffness of the foundation joint



Stiffer central section

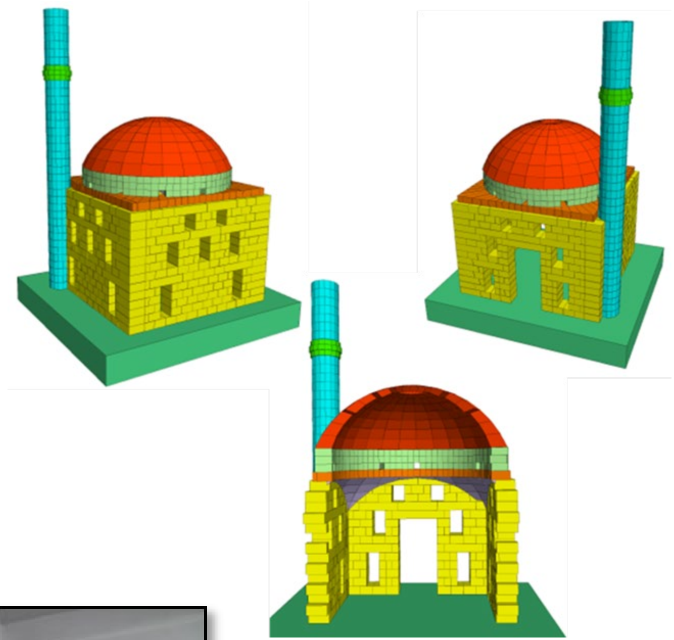
Numerical simulation: orbit of top of obelisk



Shaking table test of Skopje mosque model

(Saygili, 2014; Catki et al. 2016)

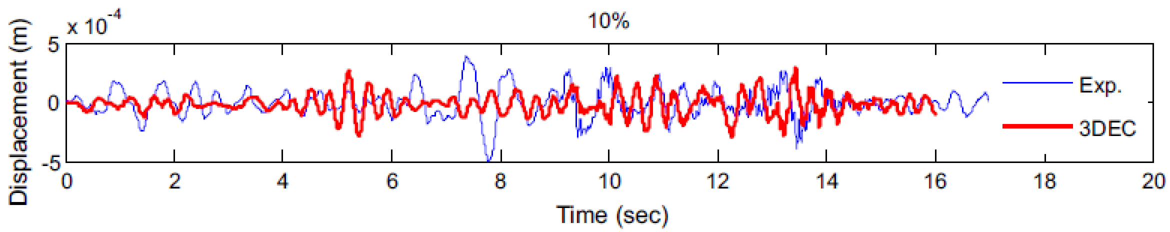
- Dynamic analysis of shaking table tests of 1:10 scale model (minaret 42 m high)
- 3DEC rigid block model
- Seismic input: Montenegro 1979 earthquake (0.4g), scaled from 10% to 250%
- Numerical model reproduces global behavior and damage patterns

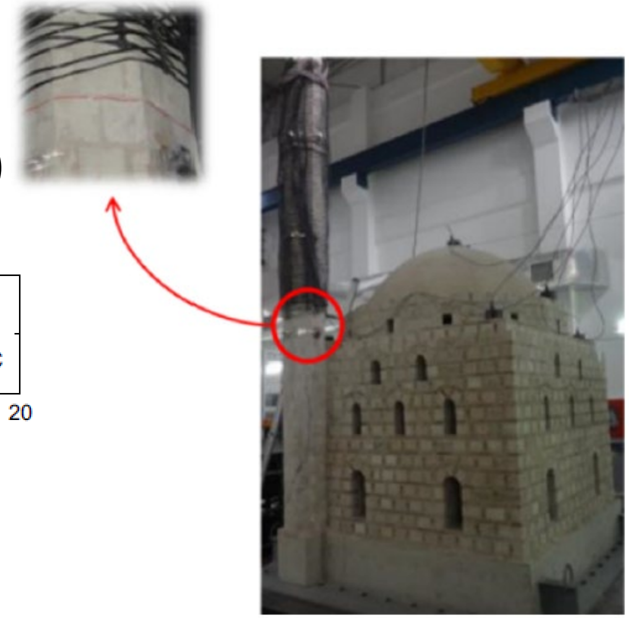


Shaking table tests at Bogazici University, Istanbul

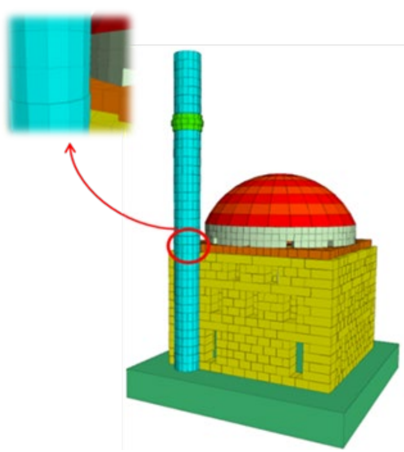
Response at top of minaret

- Test with 10% Montenegro 1979 earthquake (0.04g)

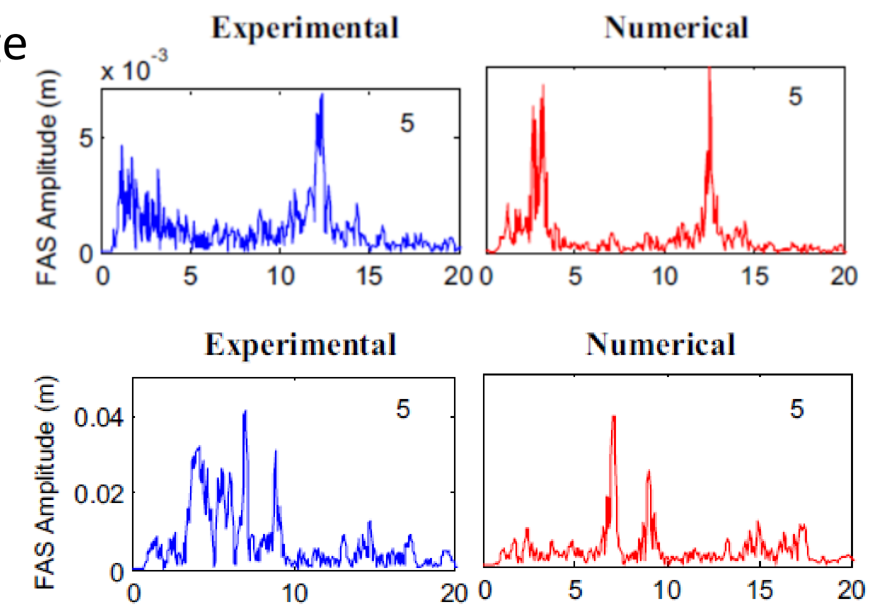




- Amplitude spectrum of response shows the change in structural frequencies, mostly due to damage in the minaret-wall connection

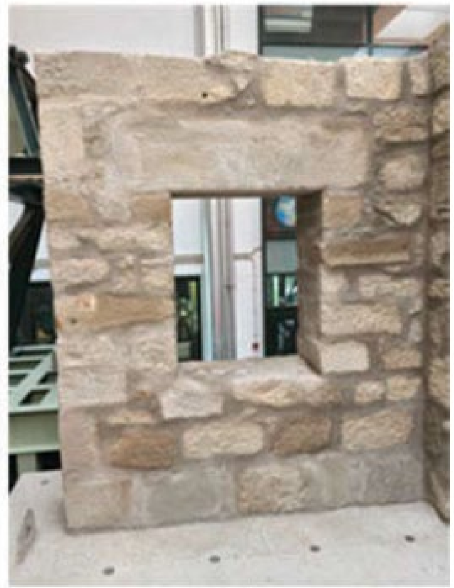


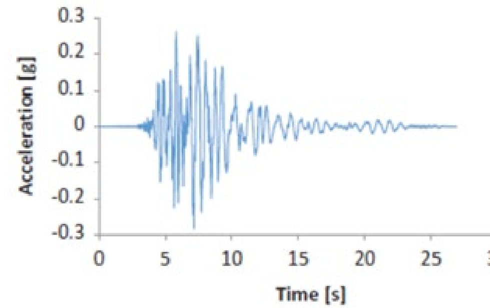
- 10% input (0.04g)
- 100% input (0.4g)



Catki et al. 2016

Shaking table tests of stone masonry house (1:1 scale model)

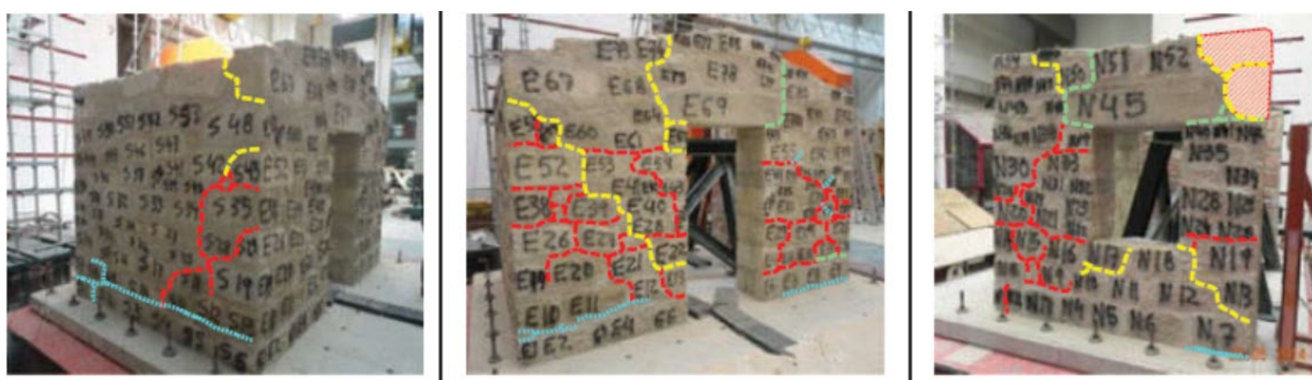




Seismic input: New Zealand 2011 earthquake, scaled in 5 stages, up to 1.05g

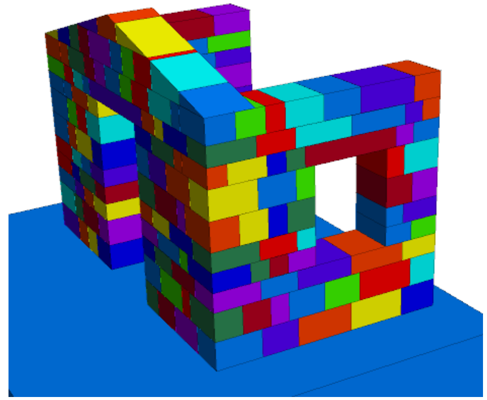
Test predictions with various models: Lourenço et al. (2017), Int. J. Arch. Heritage

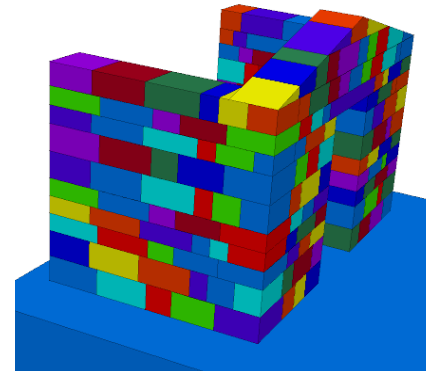
Shaking table tests at LNEC, Lisbon



After TEST05 – 1.05 g

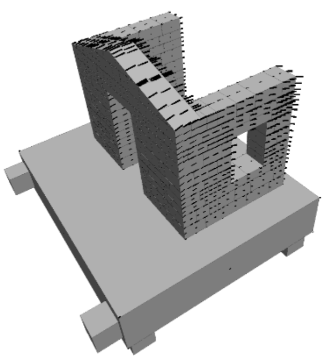
3DEC model



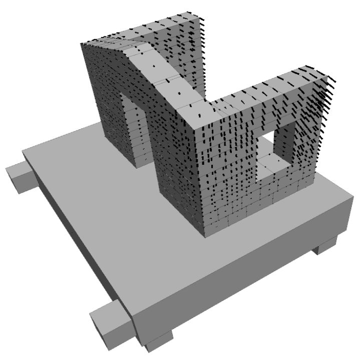


- Rigid block model
- Simplified geometry
    - Horizontal joints
    - Single leaf walls (instead of double leaf)
    - Average block sizes
- Joint stiffness calibrated to approximate measured natural frequencies

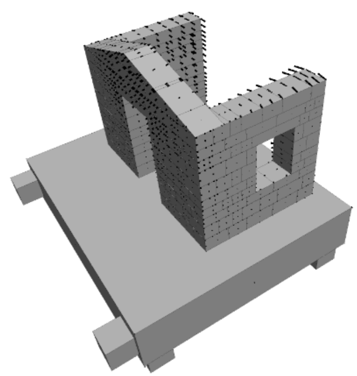
mode	exper.	numer.
1	10.3	10.4
2	15.1	13.2
3	22.8	15.2
4	24.1	17.3



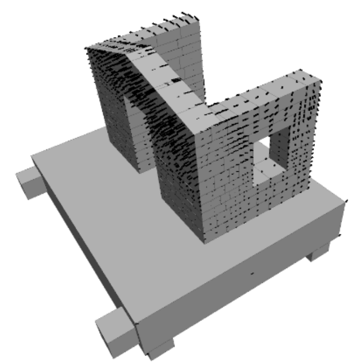
Mode 1



Mode 2

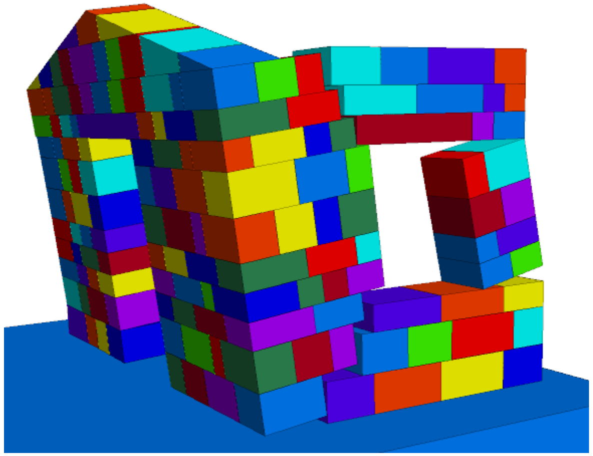


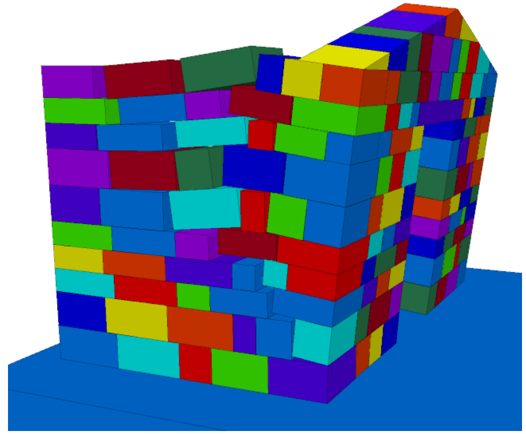
Mode 3



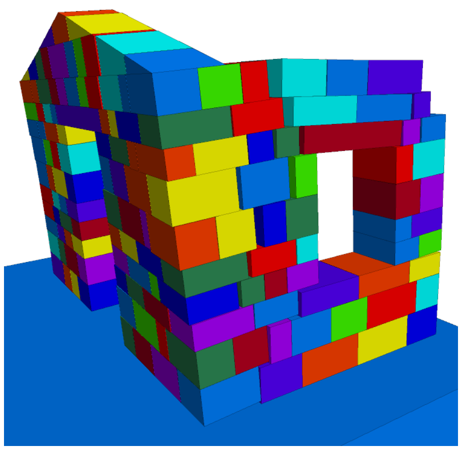
Mode 4

Pushover failure mode (0.65g)

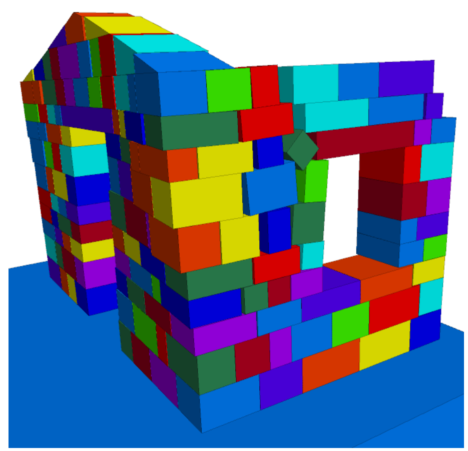




Dynamic analysis – stage 5 (1.05g)



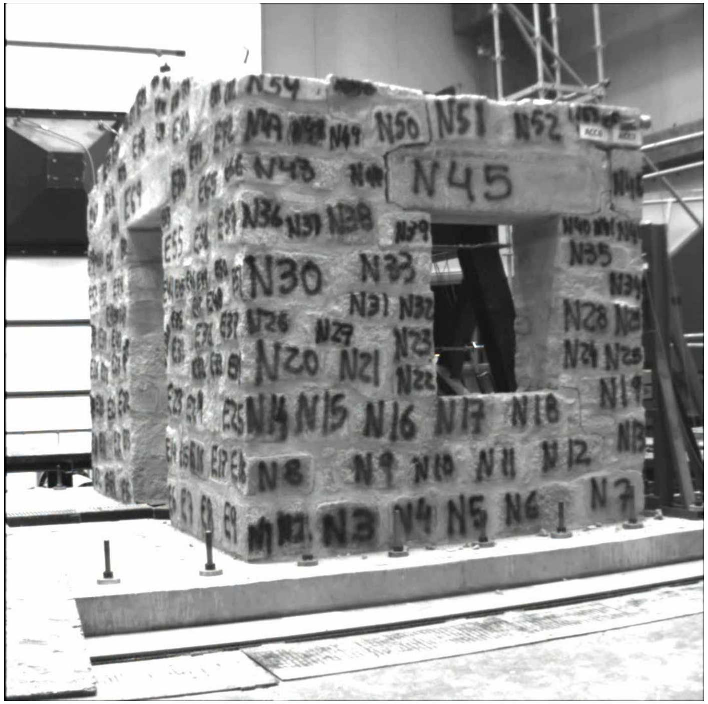
Instant of maximum displacement
(max. disp. = 175 mm)

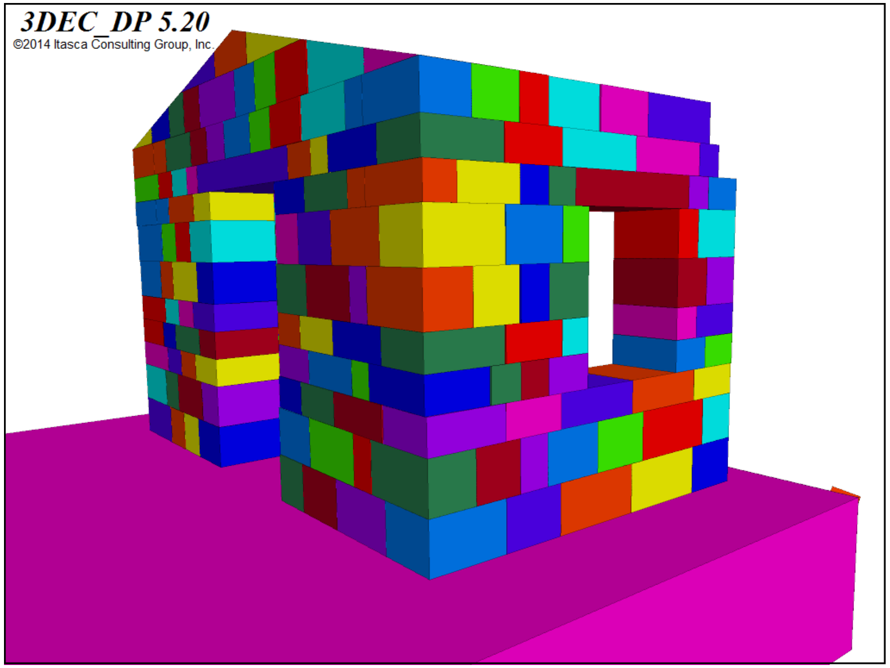


Final configuration
(max. disp. = 92 mm)

Final shaking table test
(1.05g)

Dynamic test – Stage 5





Concluding remarks

- DEM models have shown a very good performance in the analysis of various types of masonry, in particular stone block structures
- Rigid block models remain the most efficient option for dynamic analysis
- For historical constructions, in situ characterization of the dynamic behavior is essential to calibrate models
- Given the intrinsic variability of response, multiple simulations under various seismic records are advisable for safety assessment