Technical University of Crete

Co-funded by the Erasmus+ Programme of the European Union

Development of master curricula for natural disasters risk management in Western Balkan countries

NatRisk

Structural analysis of monuments

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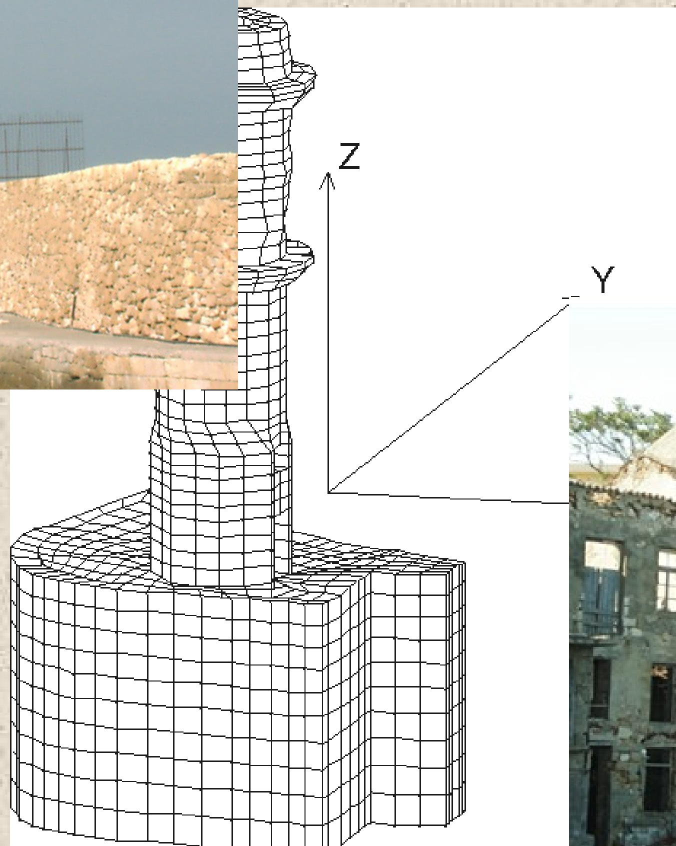
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Structural analysis of monuments

- Natural disasters (earthquakes)
- Analysis of historic structures
- Material
- Structural analysis of existing structure
- New technologies for methods of protection, strengthening.

Natural disasters (earthquakes)

- Design spectrum according aseismic codes

(valuation of this structures, life of the structure)

- Analysis of structure for records of earthquakes, critical for every structure.

Analysis of Historical Structures
Prerequisites

- Knowledge of structural problems

(degradation & damages deriving from natural or human-imposed phenomena, unsuccessful restorations) → *observation & recording*

- Knowledge of structural characteristics

(rigidity, material strength – more challenging to assess than in a modern structure) → *acquisition & measurement of specimens, bibliographic sources & experimental analysis*

- Knowledge of future influence of every intervention on the structural system (avoidance of future damages) → *confirmation on the most objective model*

Analysis of Historical Structures

Target

1. Evaluation of the structure's present condition

Data Input (Geometry, Pathology) of present condition

An accurate geometry of the structure is necessary including the permanent deformations.

Weak material, cracks etc, are important for the estimation of the structural strength and dynamic behaviour.

➔ Confirmation or Rejection of initial estimations (trial and error)

➔ Guidance into Structural Restoration methods

Analysis of Historical Structures

Target

2. Evaluation of the structure's condition after the proposed restorations

- Ensure a desired degree of security

➜ avoiding spoilage of original features (static & morphological)

➜ collaboration with wider scientific teams

Material
Heterogeneous structures

- Traditional materials: masonry, concrete
- Modern materials: composites, nano materials


Byzantine wall of Chania


Plaka bridge in Epirus

General characteristics

- Complexity imposed by the heterogeneity
- Need for modern numerical solutions
- Two general approaches:

A. Study of the macroscopic structure

B. Investigation of the microscopic material and its impact on the macroscopic structure →

Homogenization methods

Homogenization

- Step 1
- Study of a Representative sample in the microscopic scale (Representative Volume Element)
- Averaging (effective) material properties

- Step 2
- Importing results in the macroscopic scale
- Solution of the equivalent homogeneous structure

Numerical/Computational homogenization

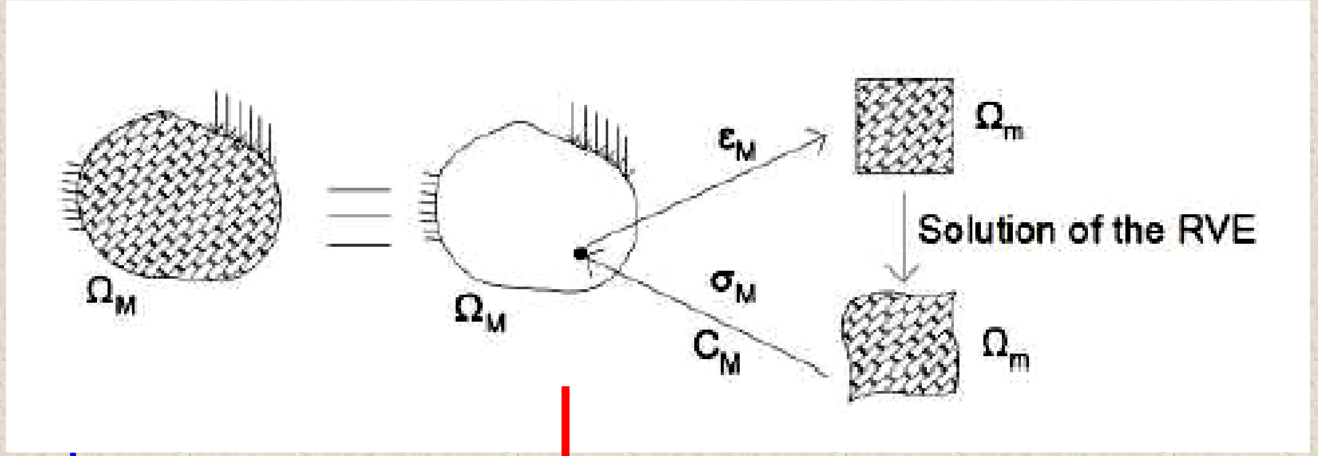
- Application in complex structures
- Increase of the computational cost
- Simulation of several non-linearities: damage, plasticity, contact

Numerical homogenization for masonry

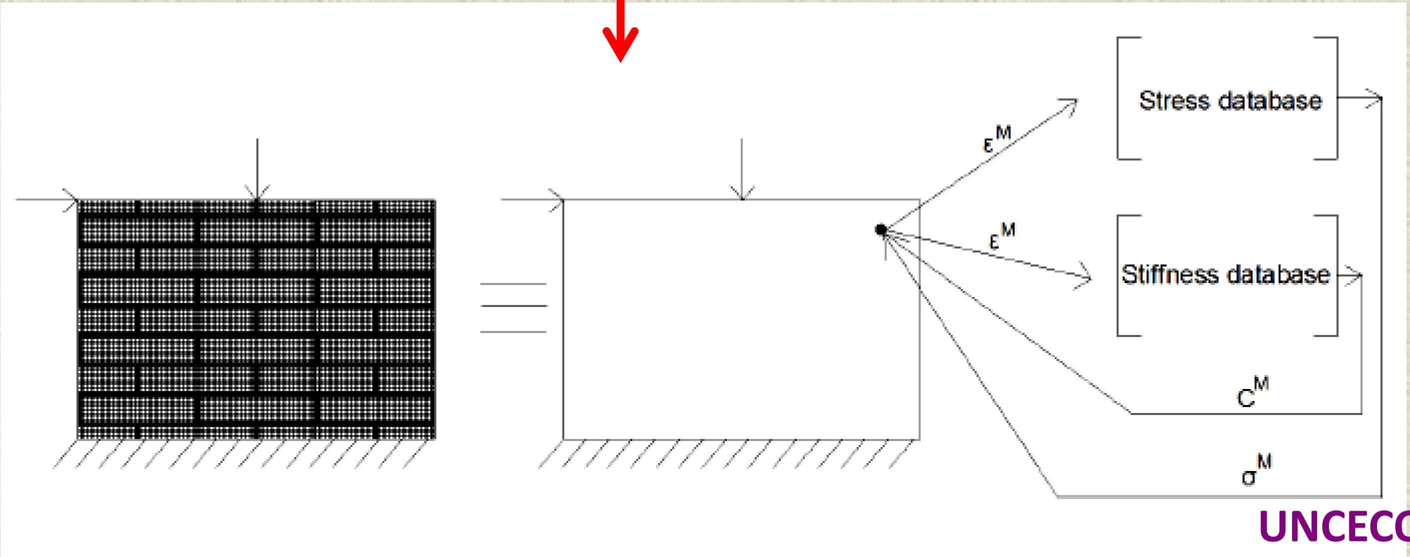
- Main idea
- Consideration of an RVE FEM in the mesoscopic scale
- Effective properties after numerical homogenization
- Usage/Comparison with a macroscopic heterogeneous masonry wall

The proposed computational homogenization scheme

Classical configuration

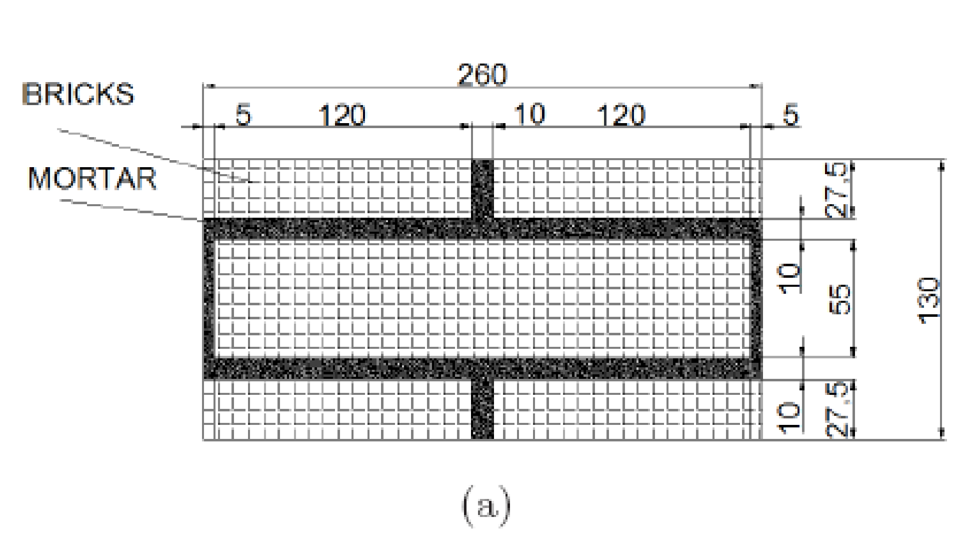


Proposed scheme

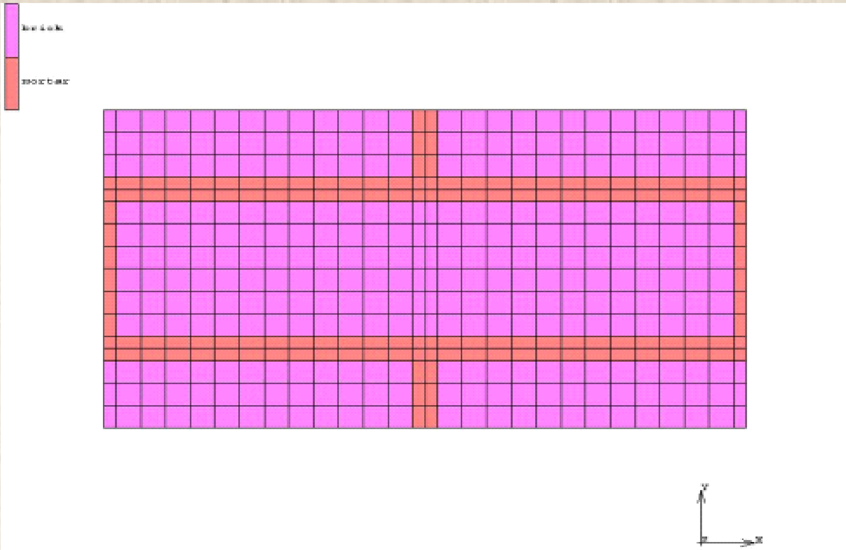


Masonry RVE

- Non-linear perfect plastic law in the mortar joints
- Linear elastic bricks
- Linear displacement boundary conditions loading



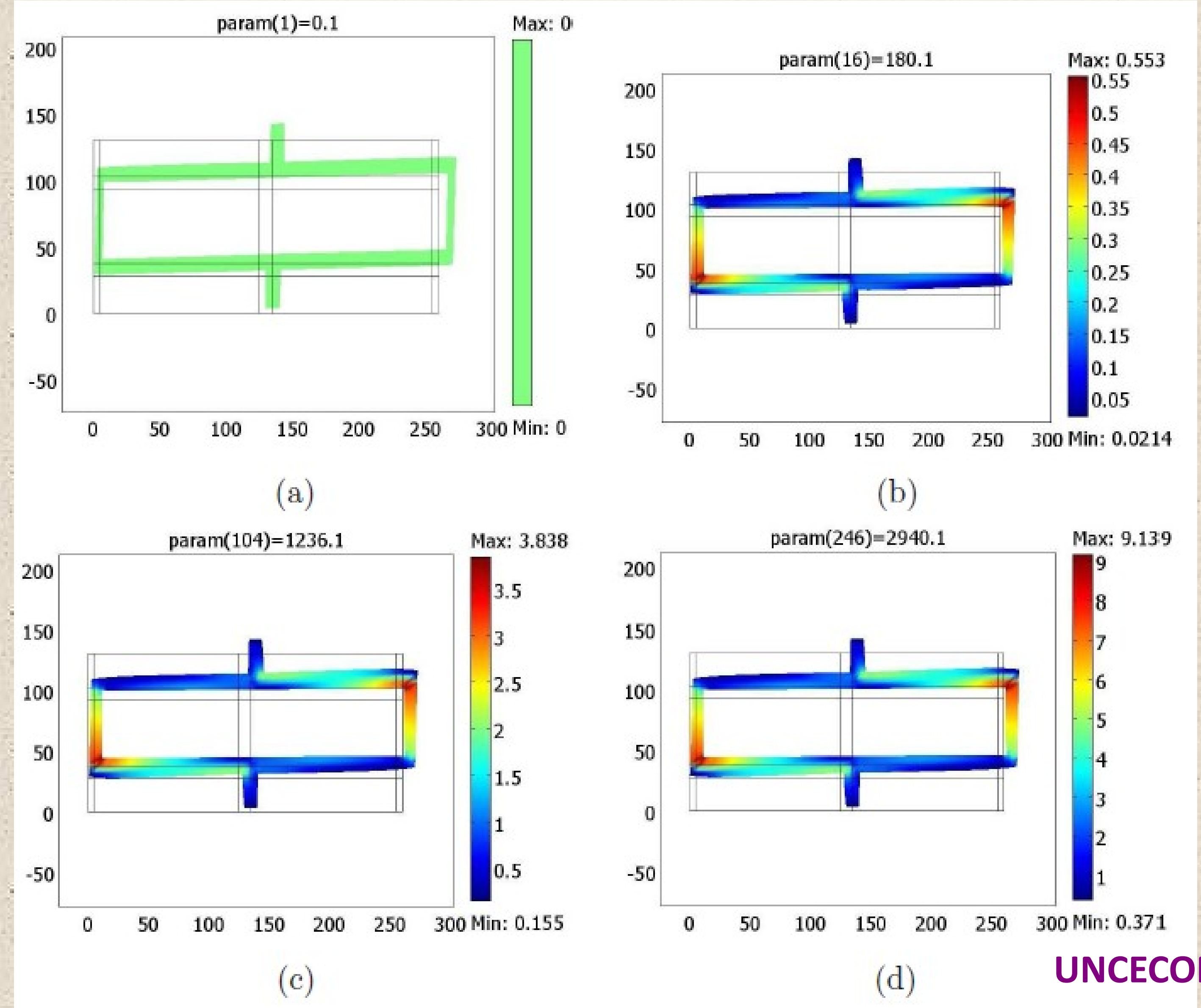
Geometry of the RVE (mm)



Mesh of the RVE

Results: micro simulations

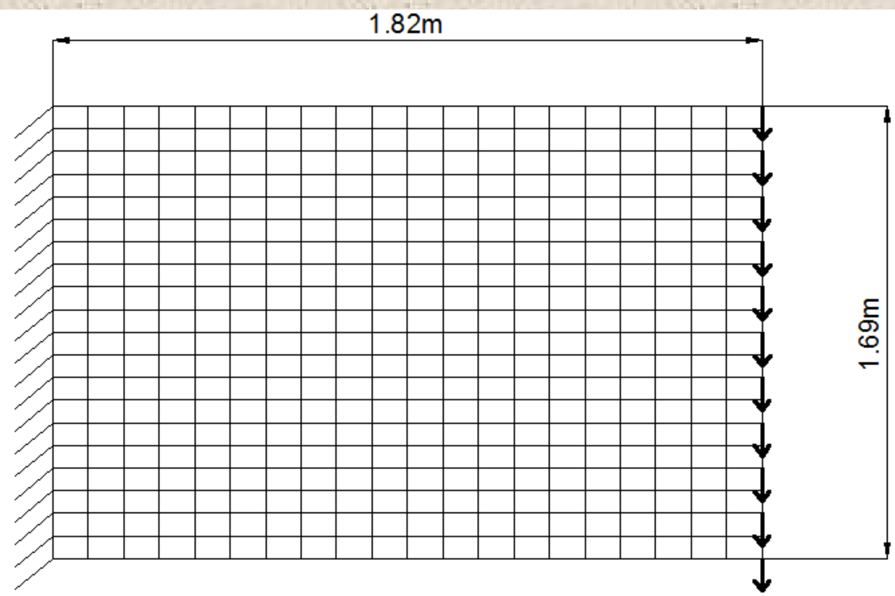
Plastic strain: gradually increased, in the mortar



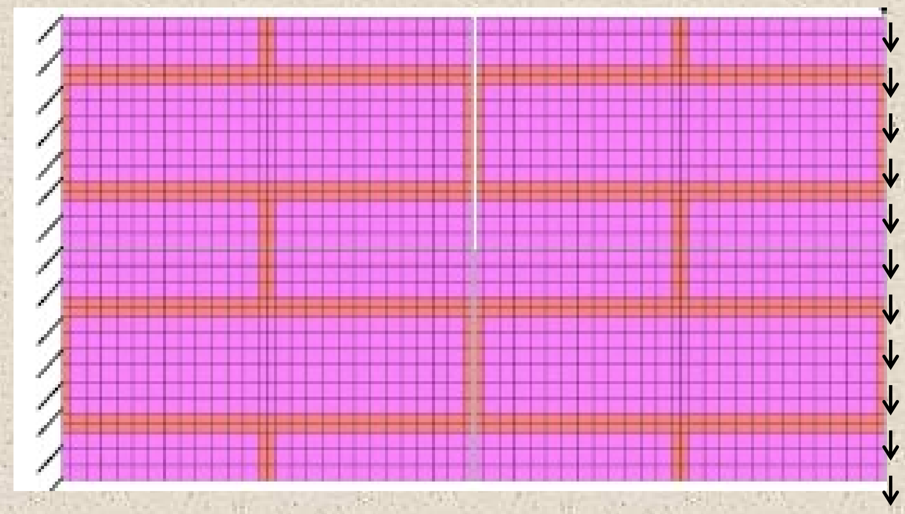
Results: overall homogenization scheme

Application 1: a masonry wall + distributed displacement of 5mm (20x20 elements)

Direct heterogeneous model: ABAQUS/MARC software



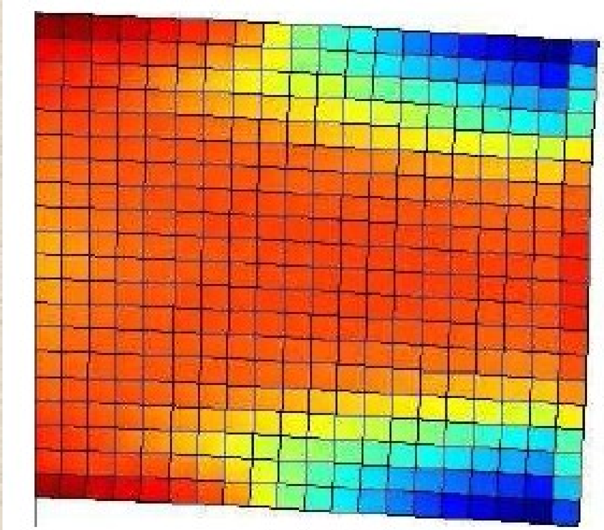
Dimensions and mesh of the proposed macroscopic, multi-scale model

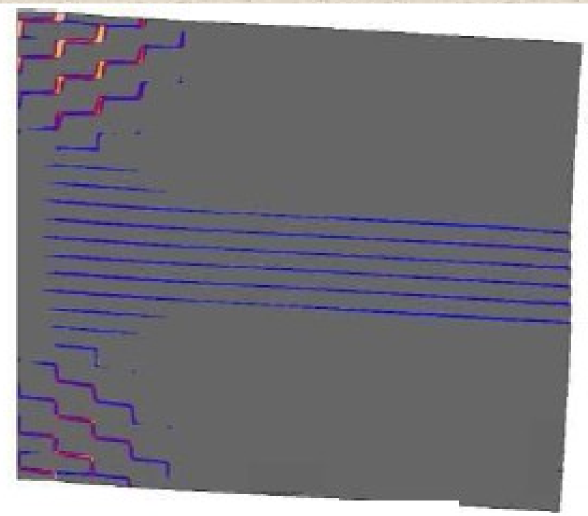


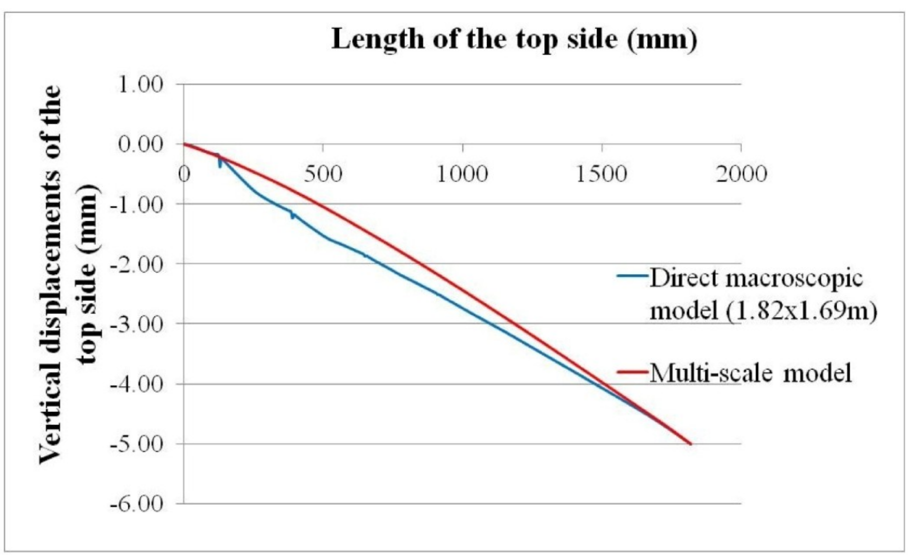
Mesh of the direct heterogeneous macroscopic model

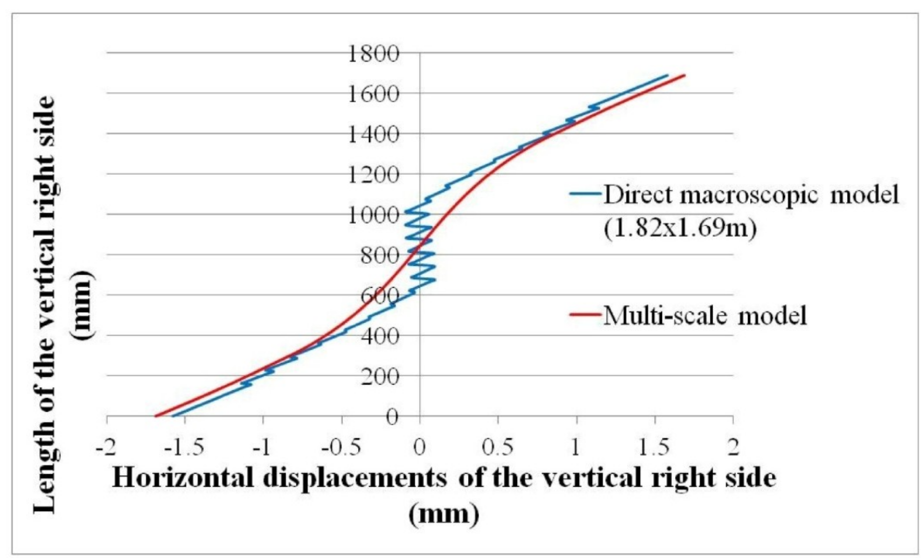
Results: overall homogenization scheme

Degradation of strength – Displacement distribution





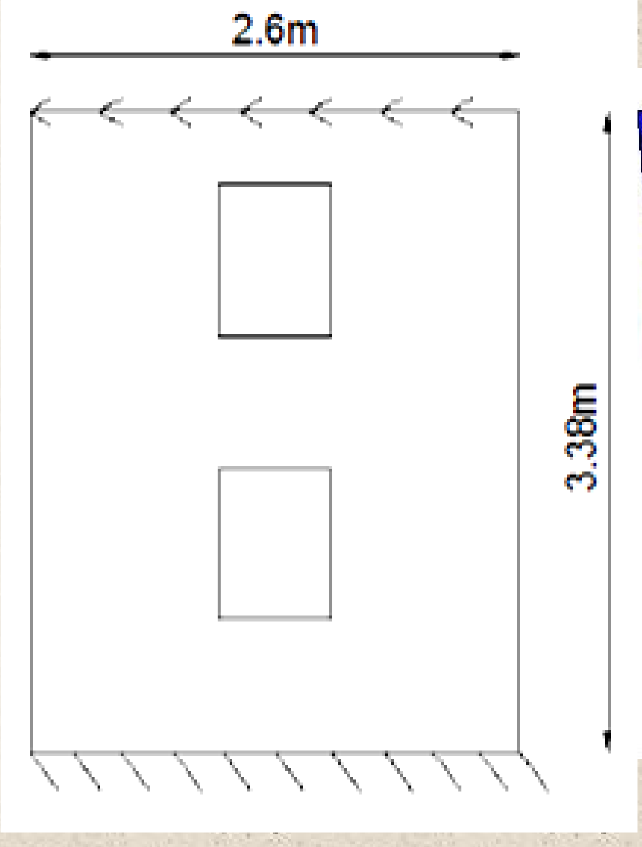


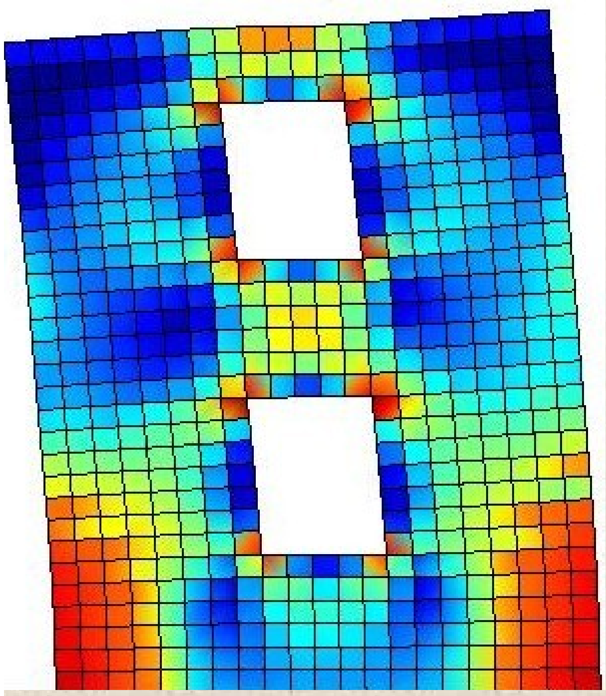


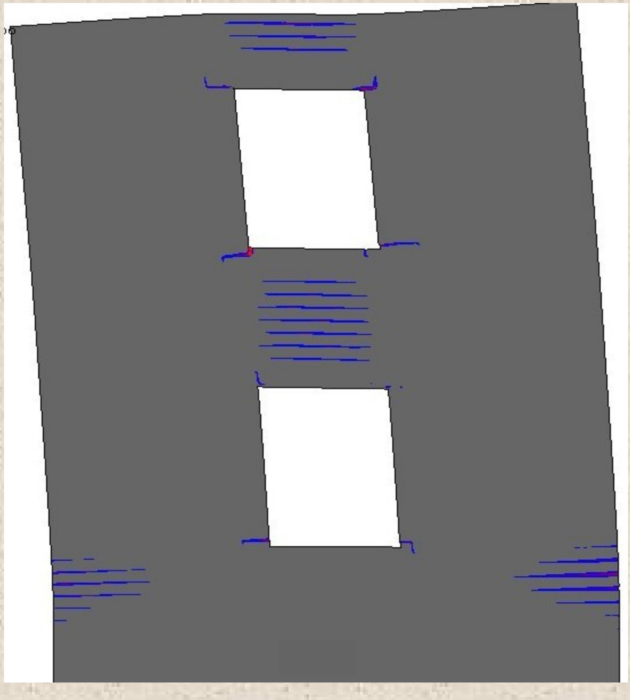
Results: overall homogenization scheme

Application 2: masonry wall + openings

Degradation of strength



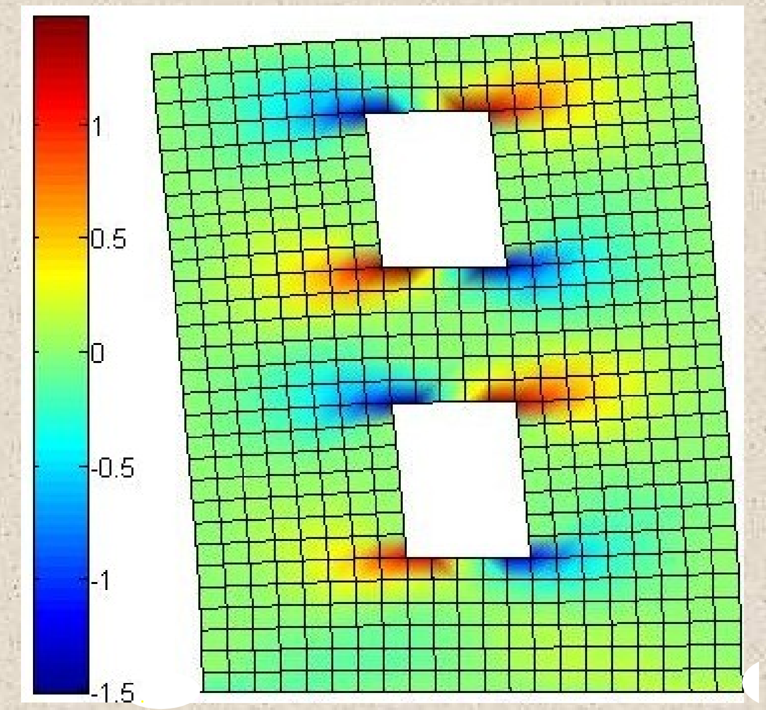




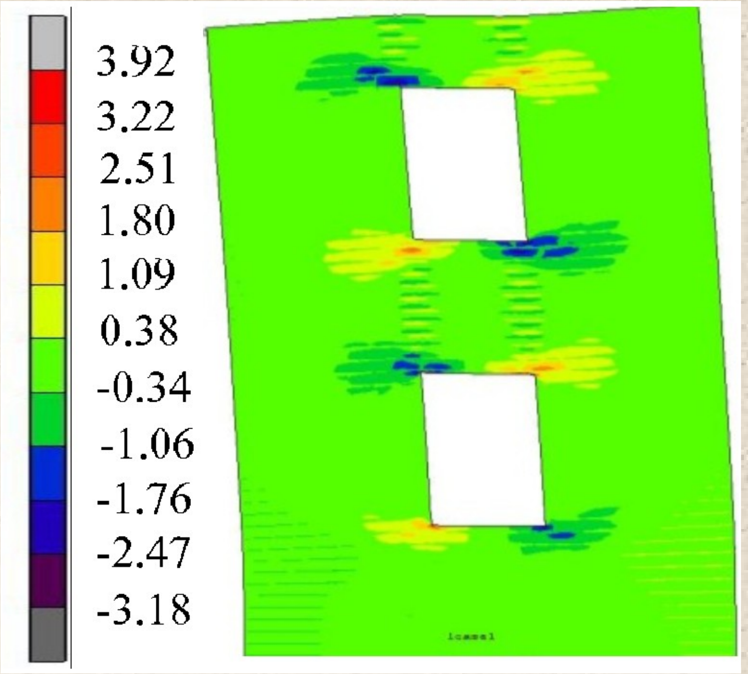
Results: overall homogenization scheme

Stresses S_{xx}

Multi-scale homogenization



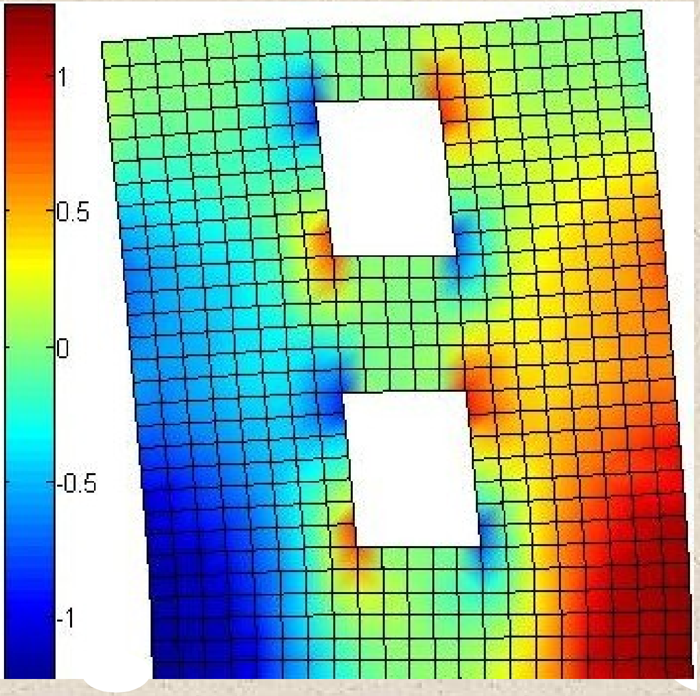
DNS model



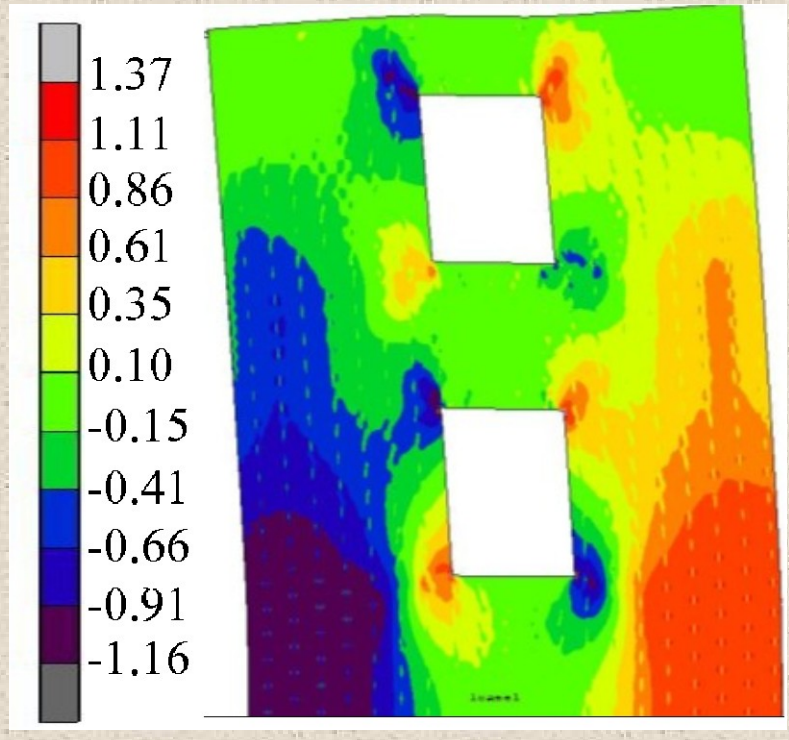
Results: overall homogenization scheme

Stresses S_{yy}

Multi-scale homogenization



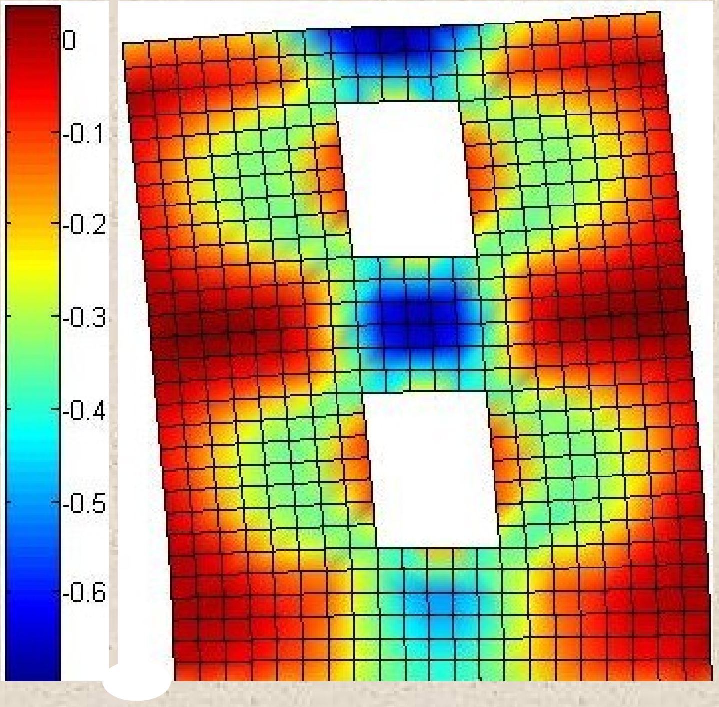
DNS model



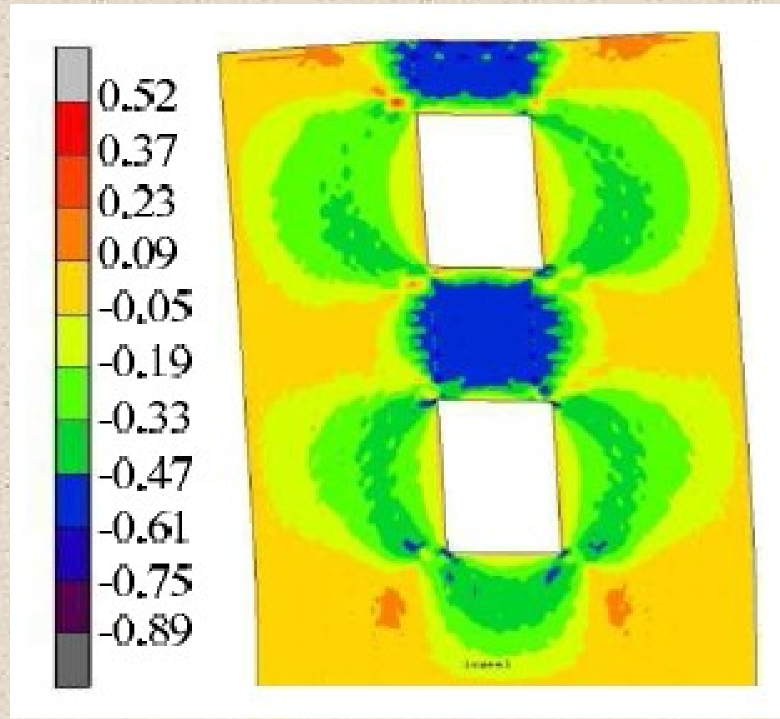
Results: overall homogenization scheme

Stresses S_{xy}

Multi-scale homogenization



DNS model



- G. A. Drosopoulos, M.E. Stavroulaki, G.E. Stavroulakis, 'Homogenization and elastic analysis of masonry walls', 10th HSTAM International Congress on Mechanics Chania, Crete, Greece, 25 – 27 May, 2013.
- Drosopoulos G.A., Stavroulaki M.E., Giannis K., Plymakis L., Stavroulakis G.E., Wriggers P. (2014), "Computational Homogenization in Masonry Structures", Proceedings of the Twelfth International Conference on Computational Structures Technology, B.H.V. Topping and P. Iványi, (Editors), Civil-Comp Press, Stirlingshire, Scotland
- Drosopoulos G.A., Koutsianitis P., Stavroulaki M.E., Riveiro B., Stavroulakis G.E. (2015), "Numerical Analysis of Masonry Structures, Taking into Account Measured Geometric and Material Data", 1st ECCOMAS Thematic Conference on International Conference on Uncertainty Quantification in Computational Sciences and Engineering M. Papadrakakis, V. Papadopoulos, G. Stefanou (eds.) Crete Island, Greece

Structural analysis of existing structures

- Data Input (Geometry, Pathology) of present condition
- Structural evaluation of a real 5 span stone arch bridge.
- 2d and 3d unilateral contact and damage models are developed.
- Terrestrial Photogrammetry is used to obtain the real, accurate geometry.

- Stavroulaki M.E., Riveiro B., Drosopoulos G.A., Solla M., Koutsianitis P., Stavroulakis G.E (2016), ‘Modelling and Strength Evaluation of Masonry Bridges Using Terrestrial Photogrammetry and Finite Elements’, *Advances in Engineering Software* 101, pp. 136-148
- Stavroulaki M.E., Riveiro B., Drosopoulos G.A., Arias P., Stavroulakis G.E. (2014), “Integrated Modeling and Evaluation of Masonry Bridges using Terrestrial Photogrammetry”, Proceedings of the Twelfth International Conference on Computational Structures Technology, B.H.V. Topping and P. Iványi, (Editors), Civil-Comp Press, Stirlingshire, Scotland
- Drosopoulos G.A., Koutsianitis P., Stavroulaki M.E., Riveiro B., Stavroulakis G.E. (2015), “Numerical Analysis of Masonry Structures, Taking into Account Measured Geometric and Material Data”, 1st ECCOMAS Thematic Conference on International Conference on Uncertainty Quantification in Computational Sciences and Engineering M. Papadrakakis, V. Papadopoulos, G. Stefanou (eds.) Crete Island, Greece

Masonry arch analysis

- Terrestrial photogrammetry or laser scanning technique :

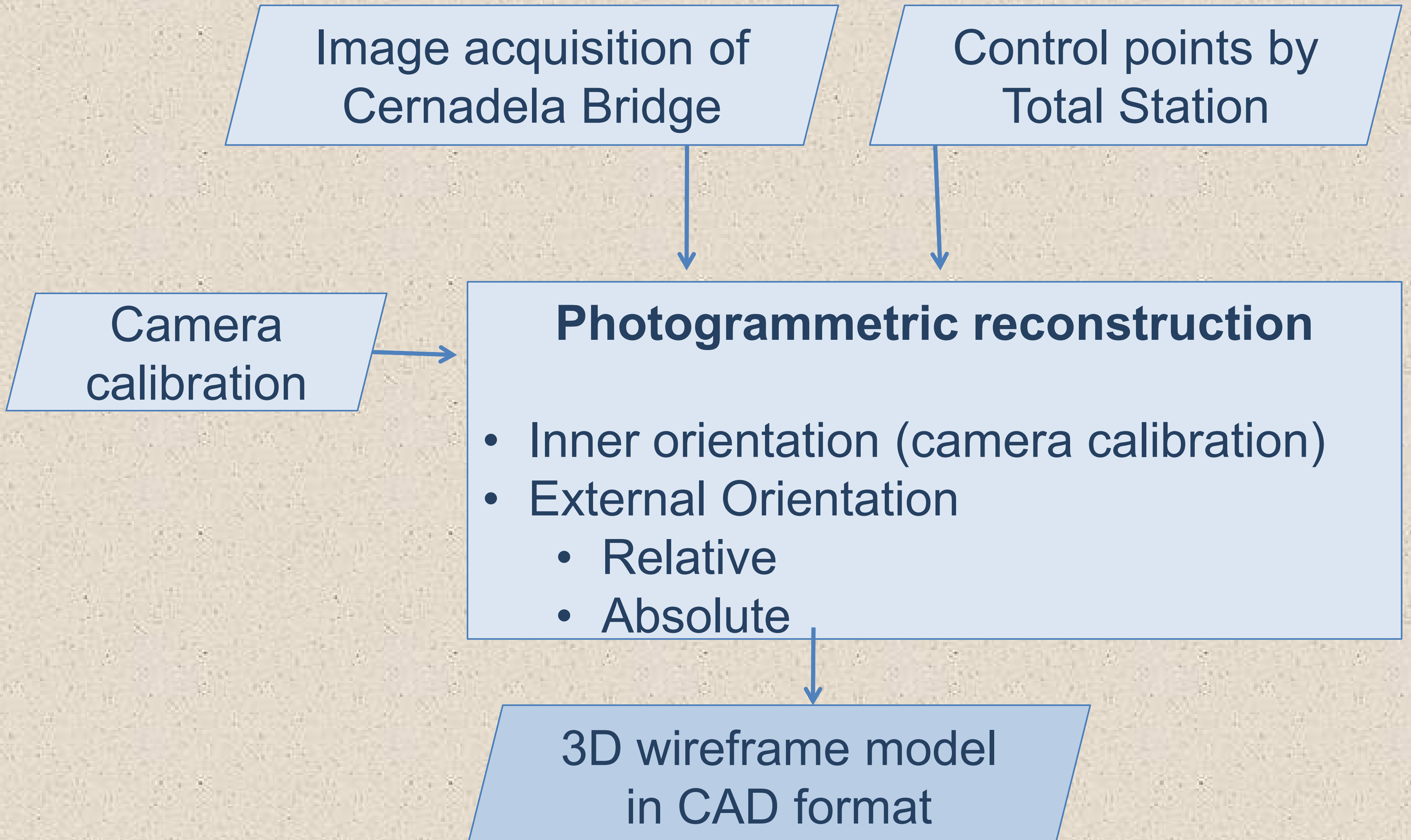
  measure the current state of the structure and the exact representation of the geometry of the structure

- Evaluation of the ultimate load and collapse mechanism using non-linear finite element analysis models:

  continuum damage mechanics,

  contact mechanics

Geometric reconstruction



Data acquisition:

Image acquisition

Topographic works

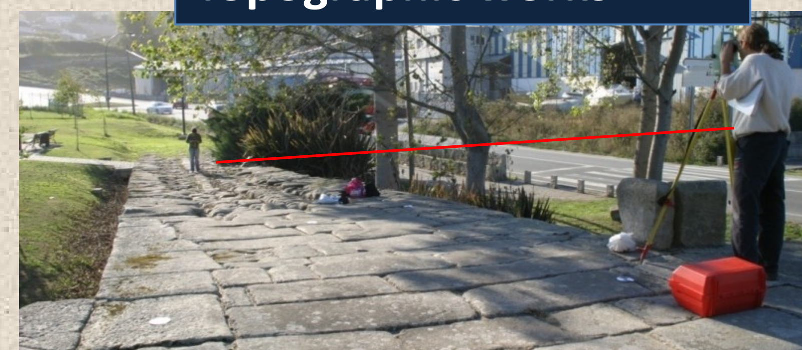
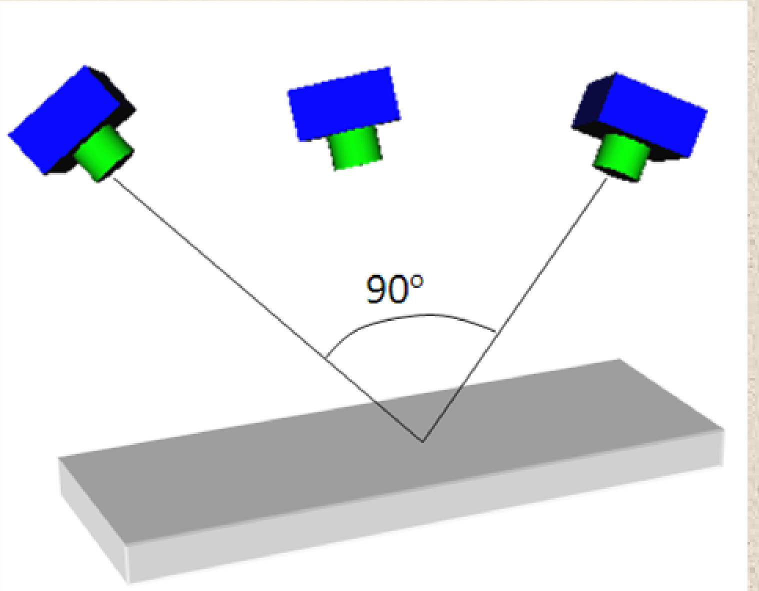
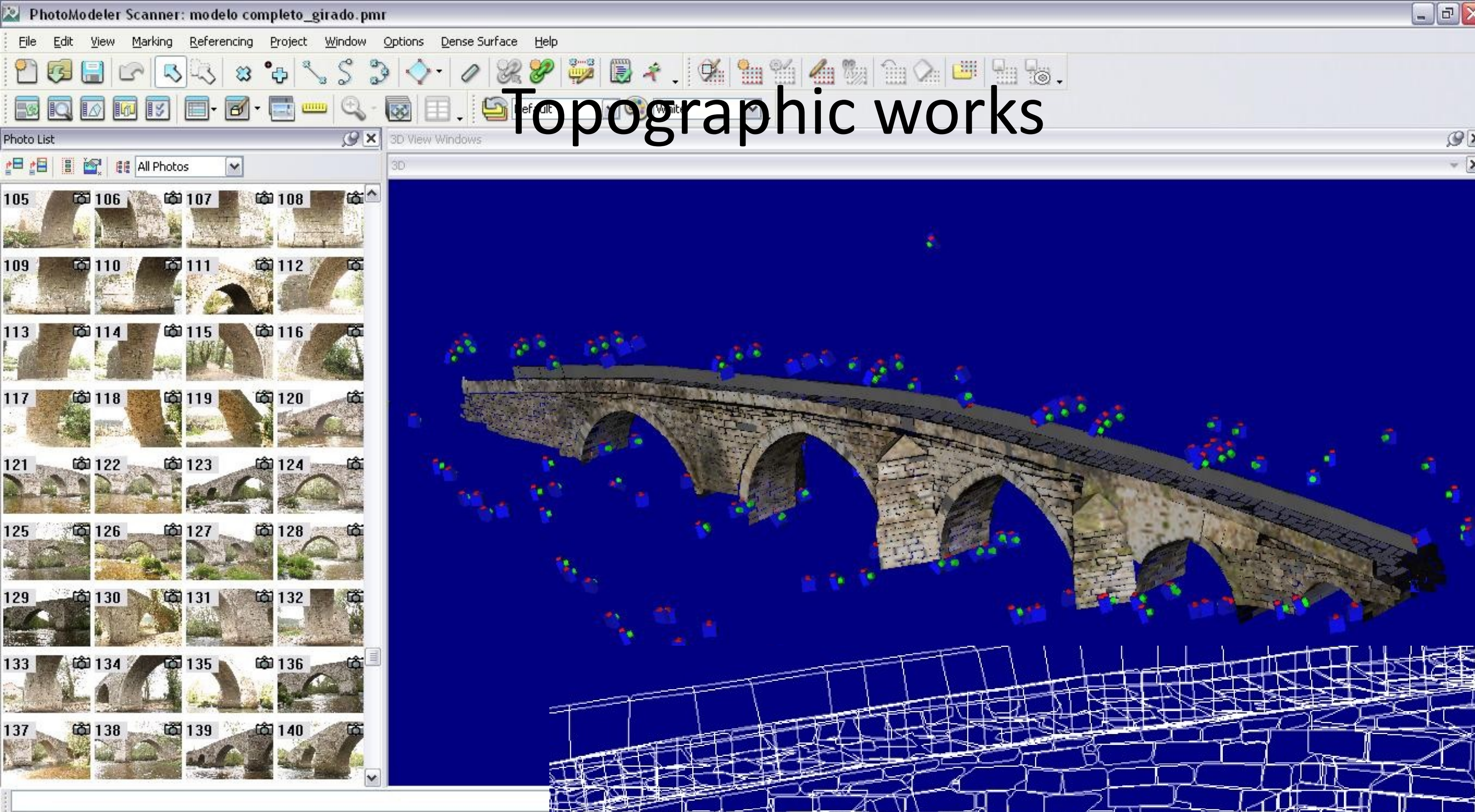
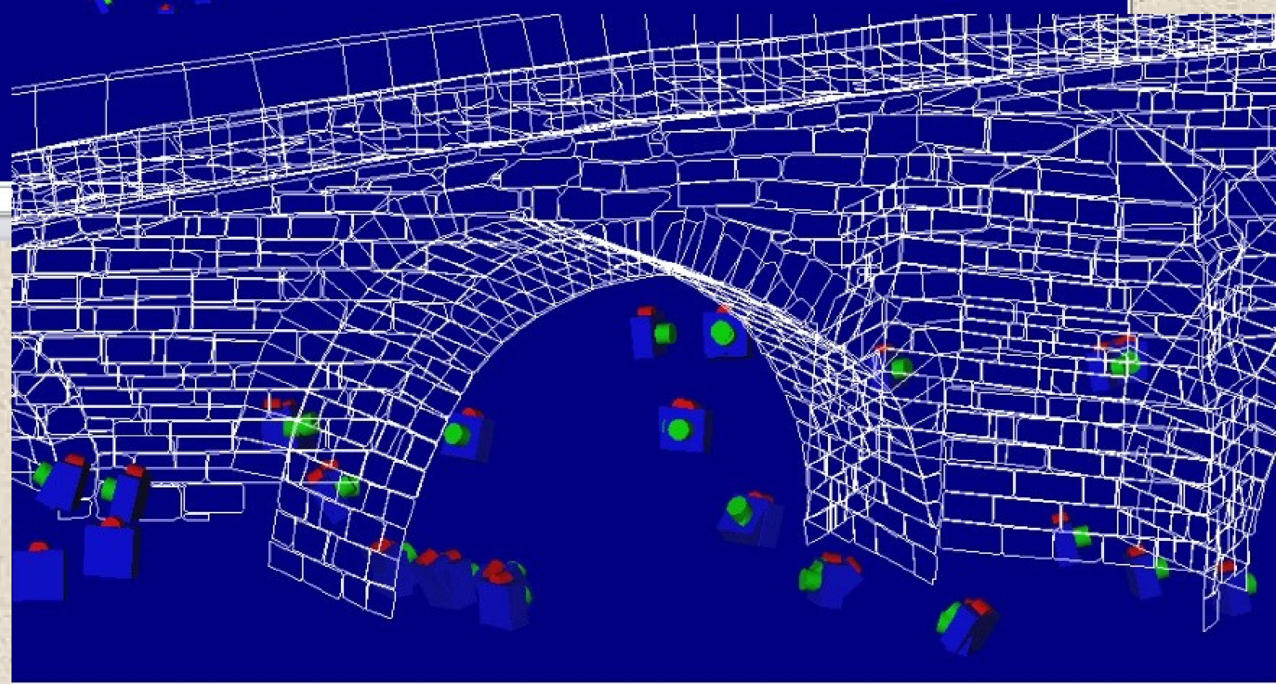


Image acqusition



Topographic works

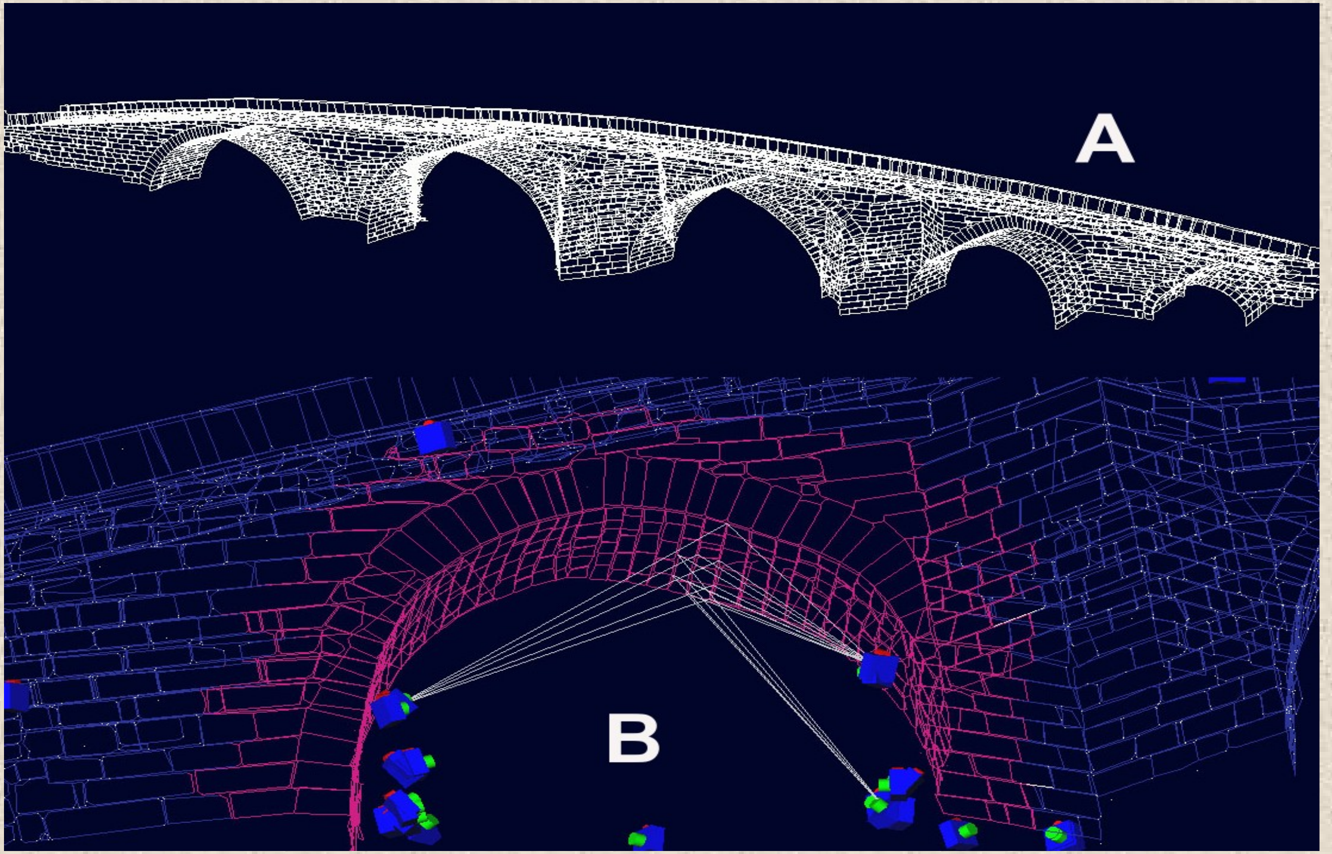




X Precision (m)	0.007
Y Precision (m)	0.008
Z Precision (m)	0.005
RMSE (m)	**0.012**
RMSE (pix)	**1.49**

FE structural evaluation of Cernadela Bridge (Spain)

Geometry

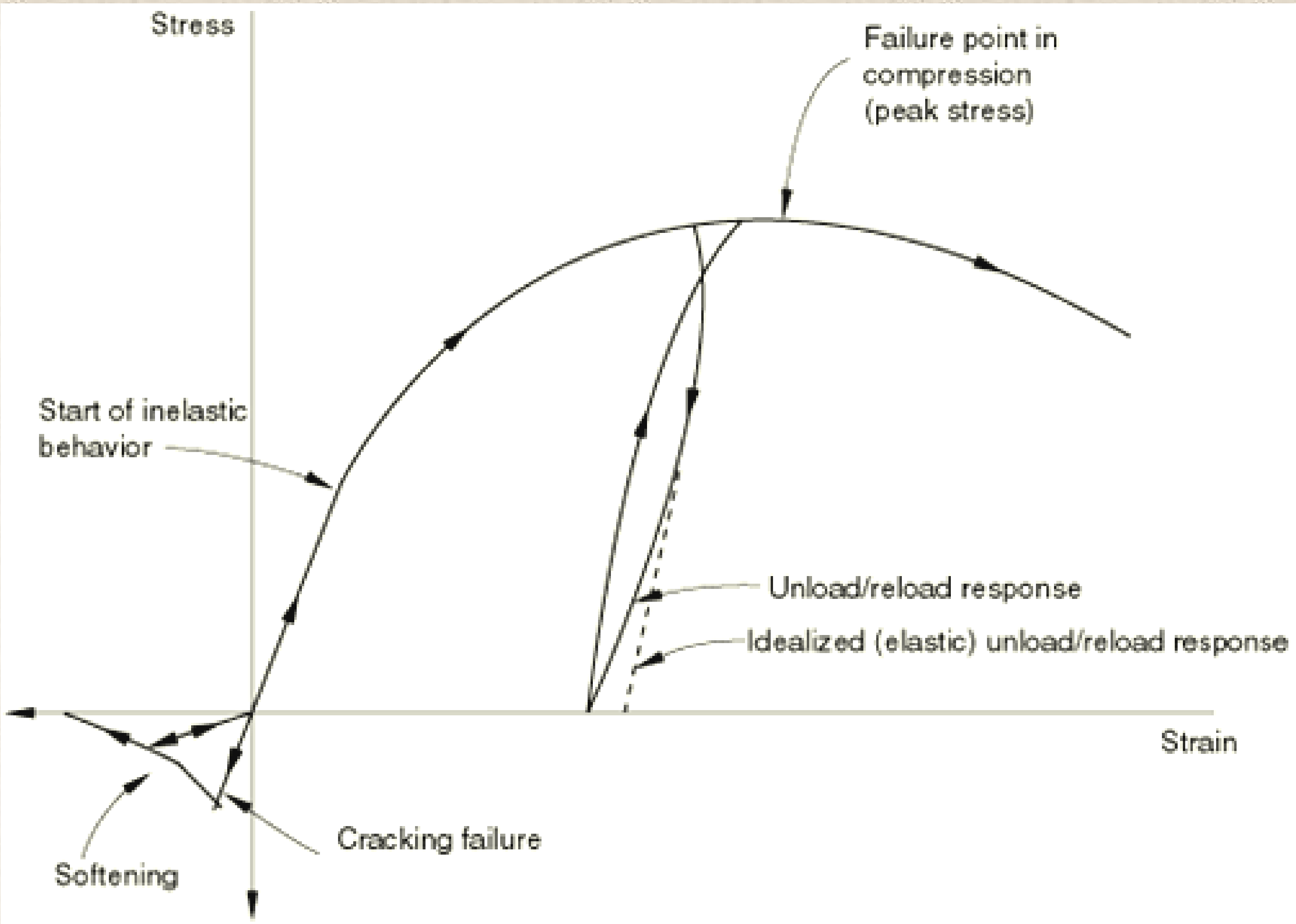


(A) 3D wireframe model of the whole structure

(B) Detailed model of second vault of the bridge with camera position and intersection rays of some points.

Continuum damage model

Smeared crack damage model



Uniaxial tensile-compressive behaviour

Masonry arches

- Non homogenous material consisted of

a) Stones (often positioned as blocks in a segmental shape)

- high strength in compression

- low strength in tension → No tension material

b) Mortar joints (frictional joints)

- generally low strength

- Geometrical form + self weight: An issue of great importance for the stability of the structure

- Usage of non – linear mechanics

Discrete model

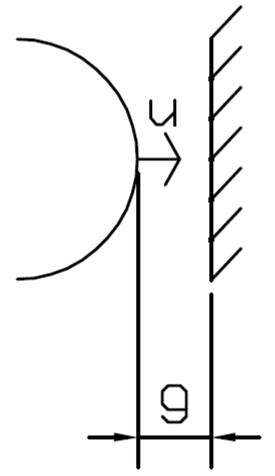
- Development of a discrete, finite element analysis model

- Contact interfaces simulating potential cracks are considered in the geometry of the bridge

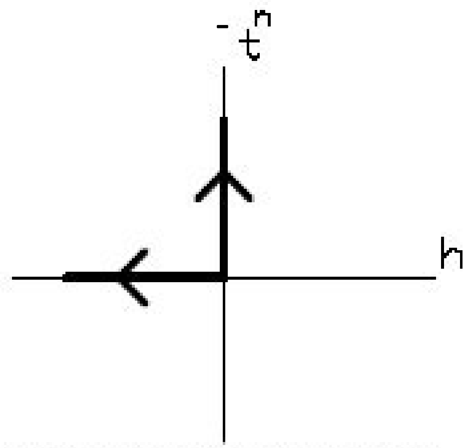
- Opening or sliding of a number of potential interfaces indicates crack initiation / propagation

- Zero tensile resistance in the normal direction of the interfaces

Unilateral contact problem



Bodies in contact



Graphical representation of the complementarity relation

$$u - g \leq 0 \Longrightarrow h \leq 0$$ → Nonpenetration relation

$$-t^n \geq 0$$ → Only compressive stresses are allowed (contact pressure)

$$t^n(u - g) = 0.$$ → Complementarity relation

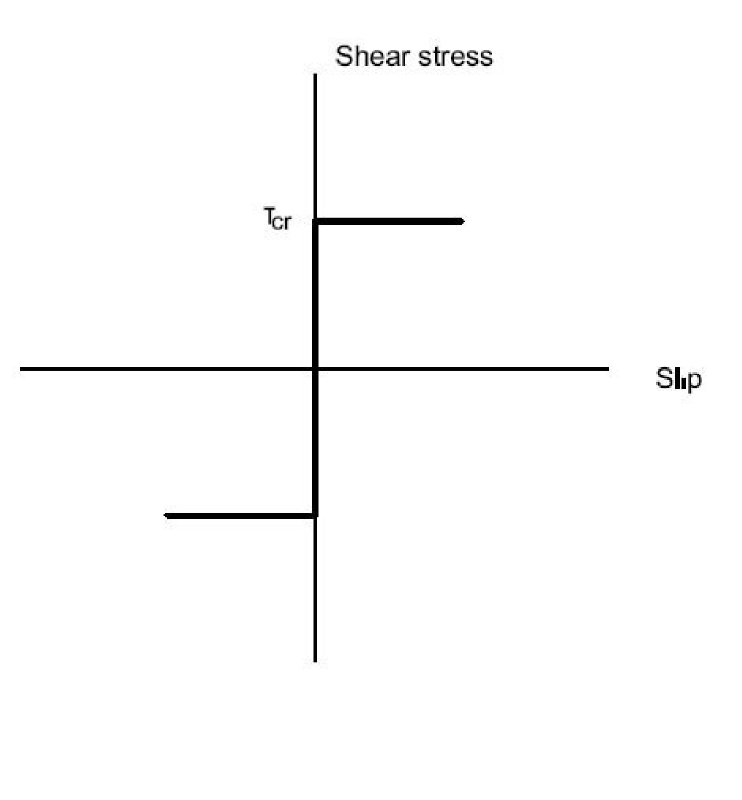
Frictional Stick-Slip problem

(Tangential direction of the interfaces)

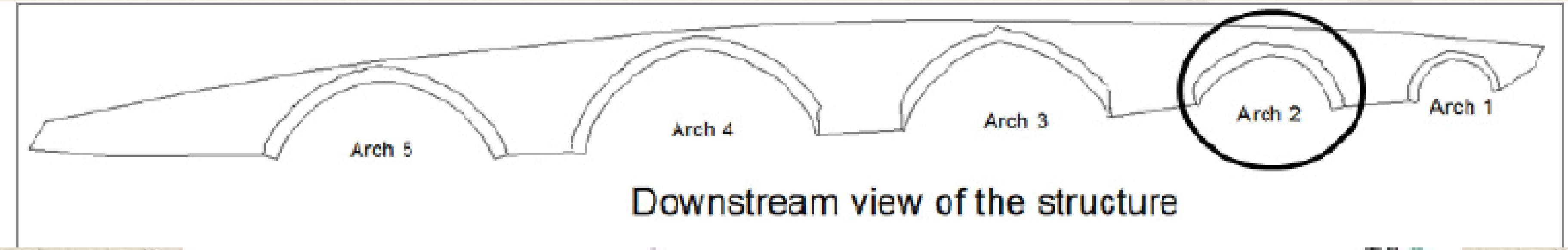
<u>Coulomb friction model</u>

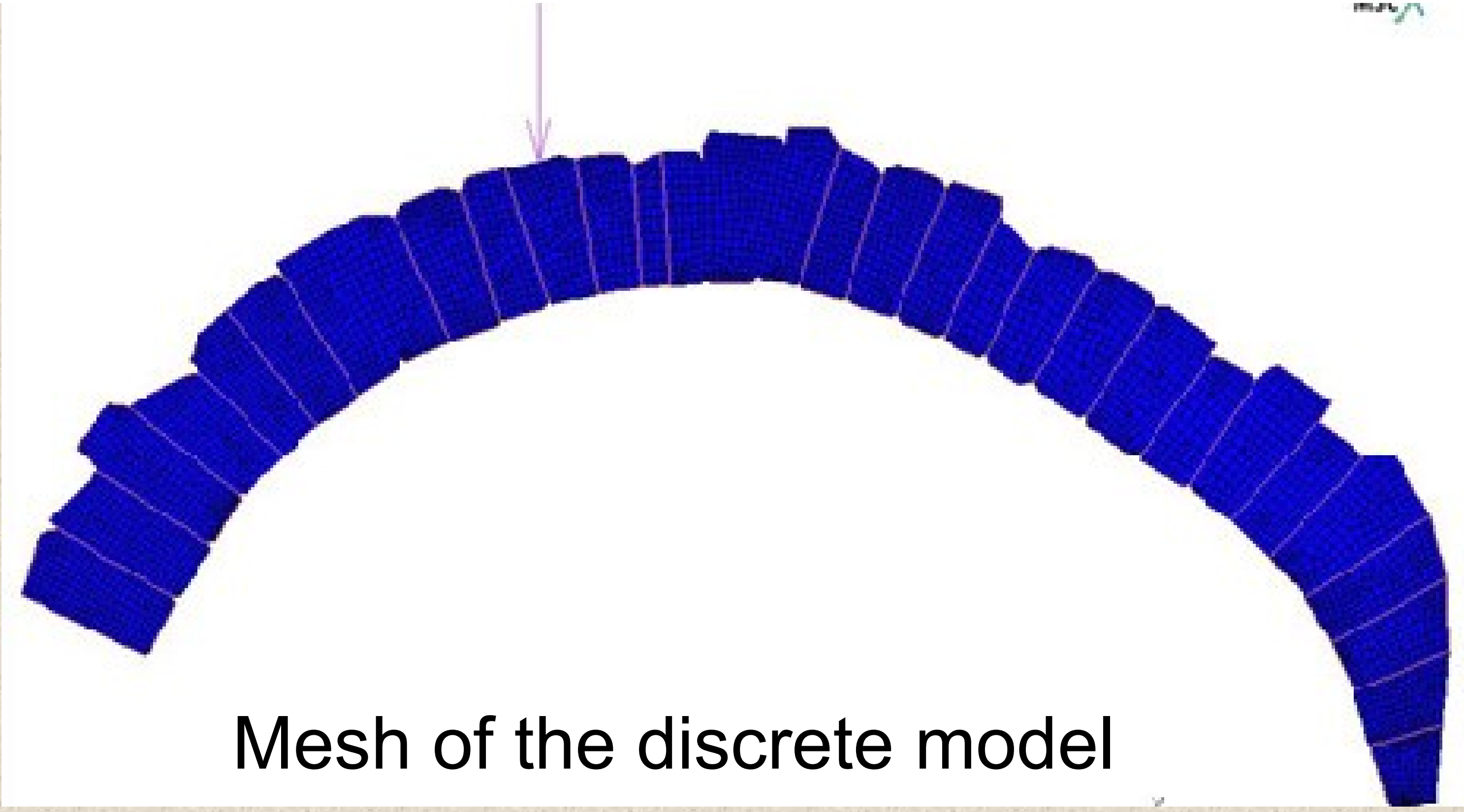
- Two contacting surfaces start sliding when $\tau_{cr} = \mu \cdot t^n$
- Stick conditions: No sliding when $\tau < \tau_{cr}$
- τ_{cr}: Critical shear stress
- μ: Friction coefficient
- t^n: Contact pressure

- Graphical representation



Single arch analysis

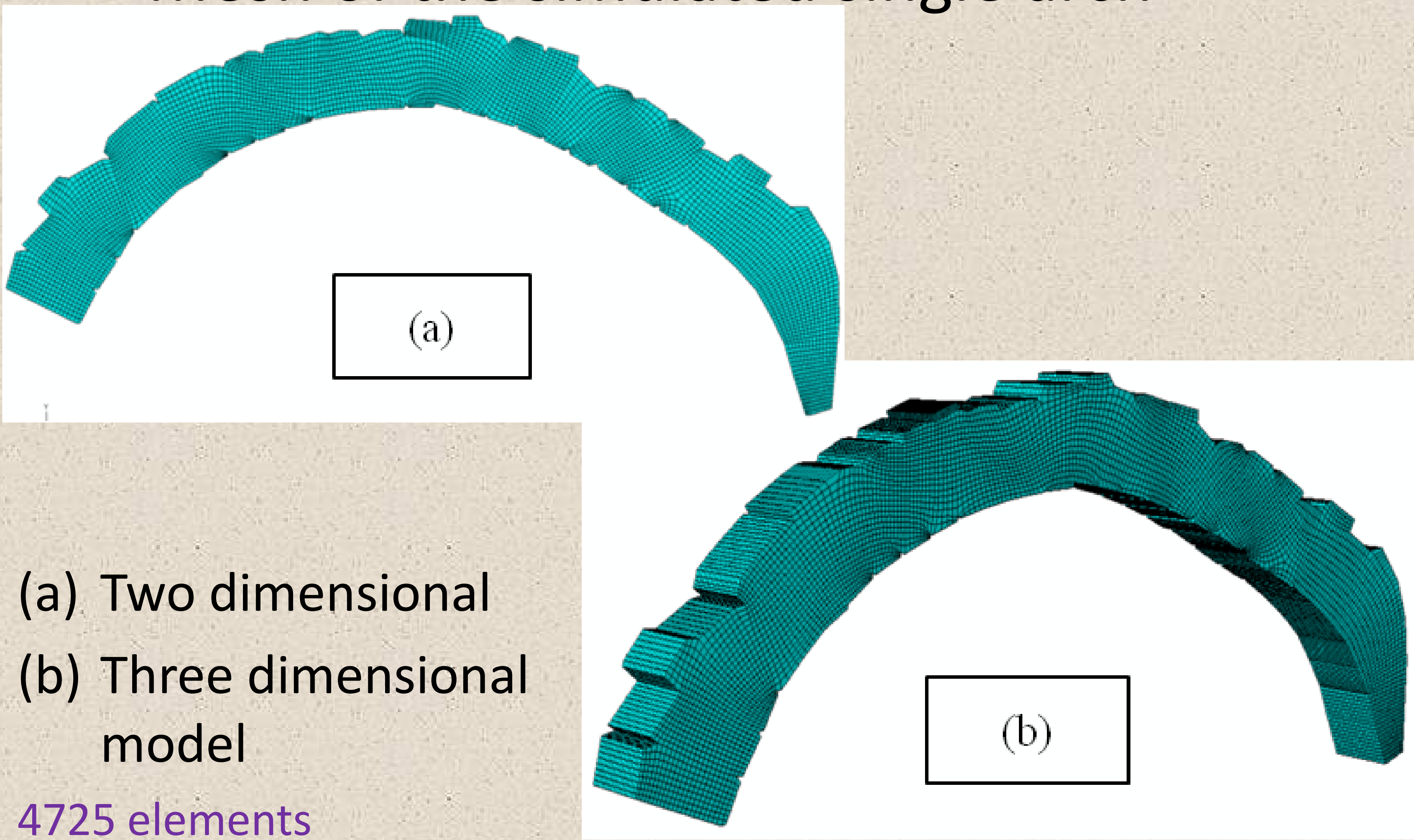




Two dimensional model of Marc. 4351 elements and 4661 nodes

Single arch analysis

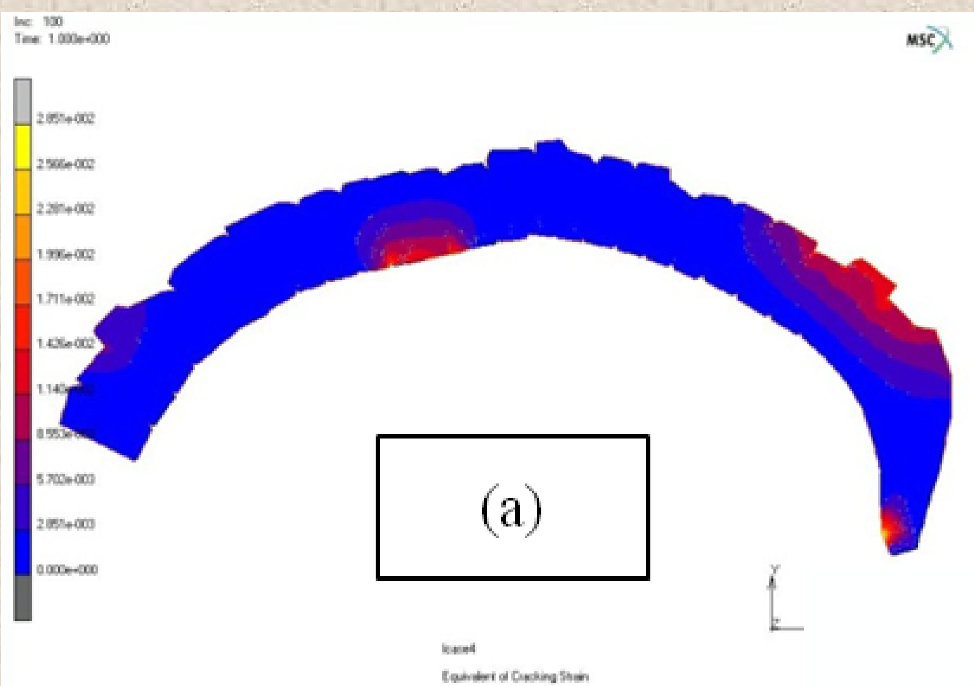
Mesh of the simulated single arch



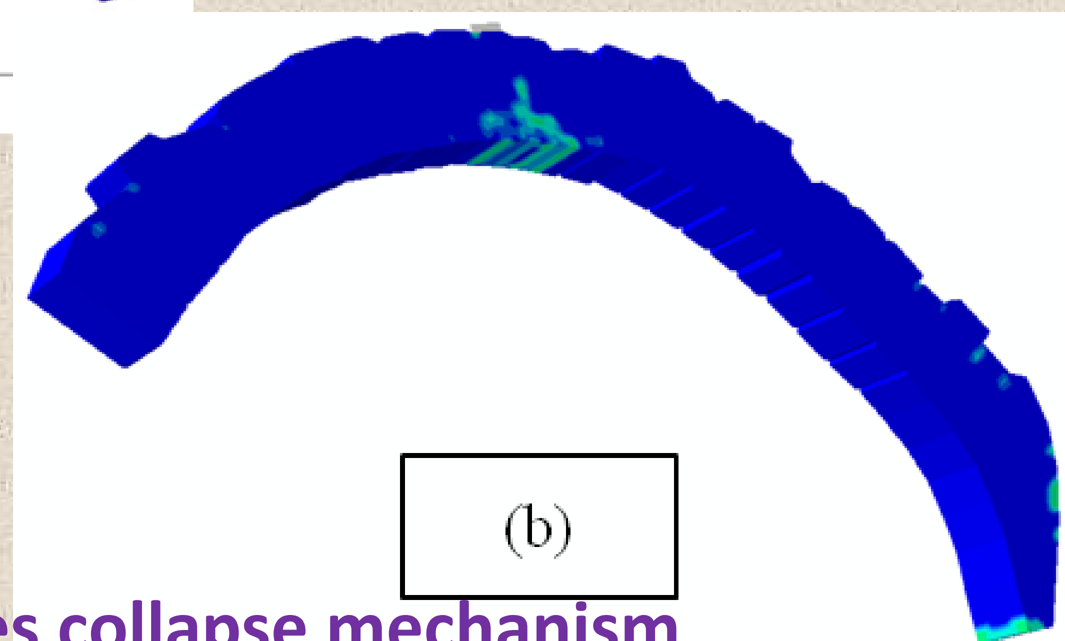
(a) Two dimensional
(b) Three dimensional model

4725 elements

Results – Continuum models



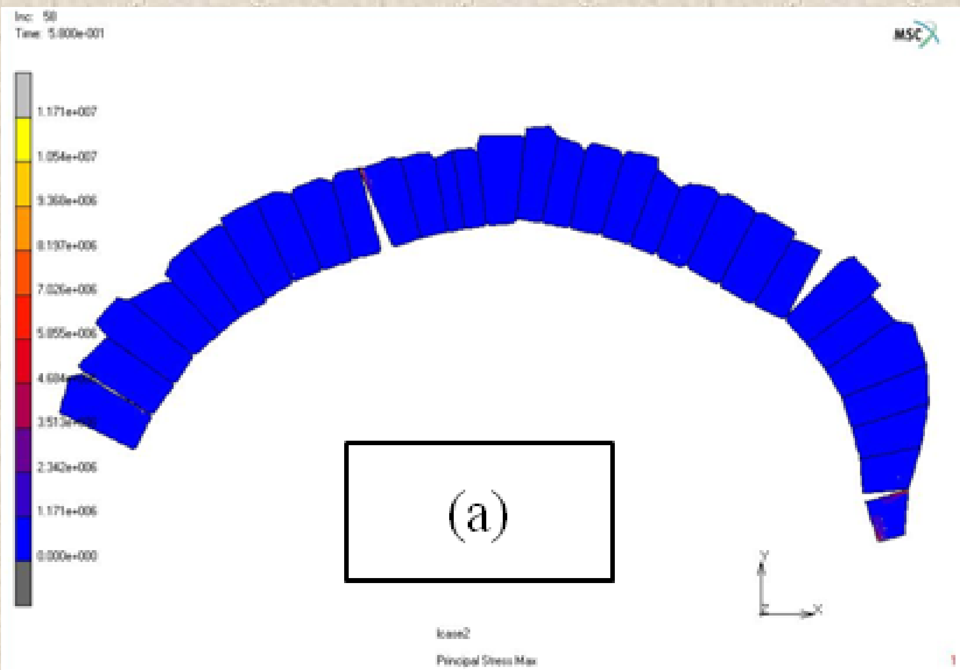
Contours of Equivalent cracking strain

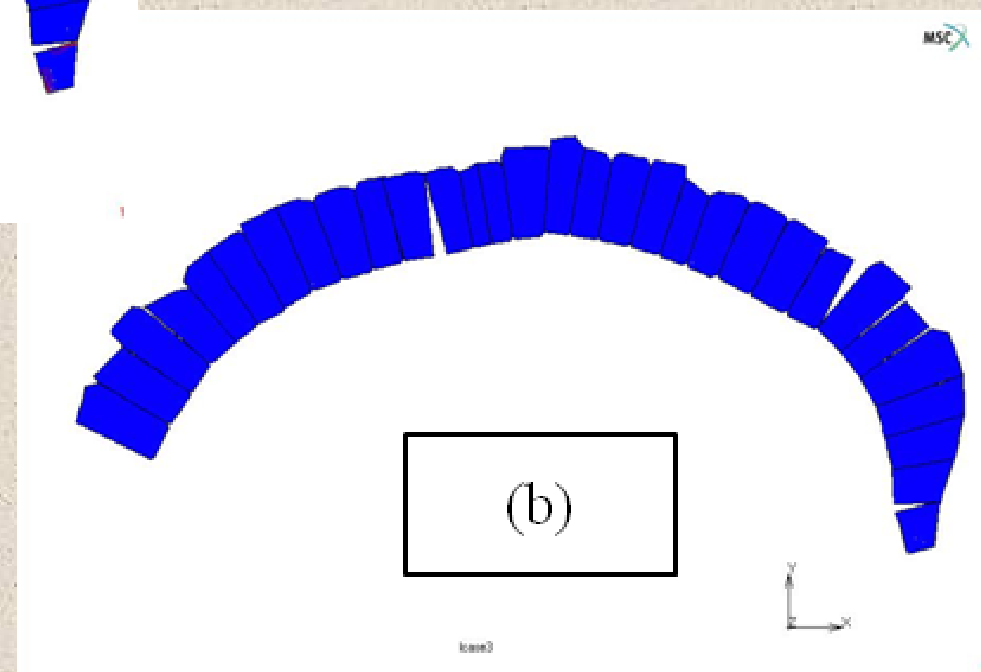


(a) 2D model
(b) 3D model

Classical 4 hinges collapse mechanism

Results – Discrete models

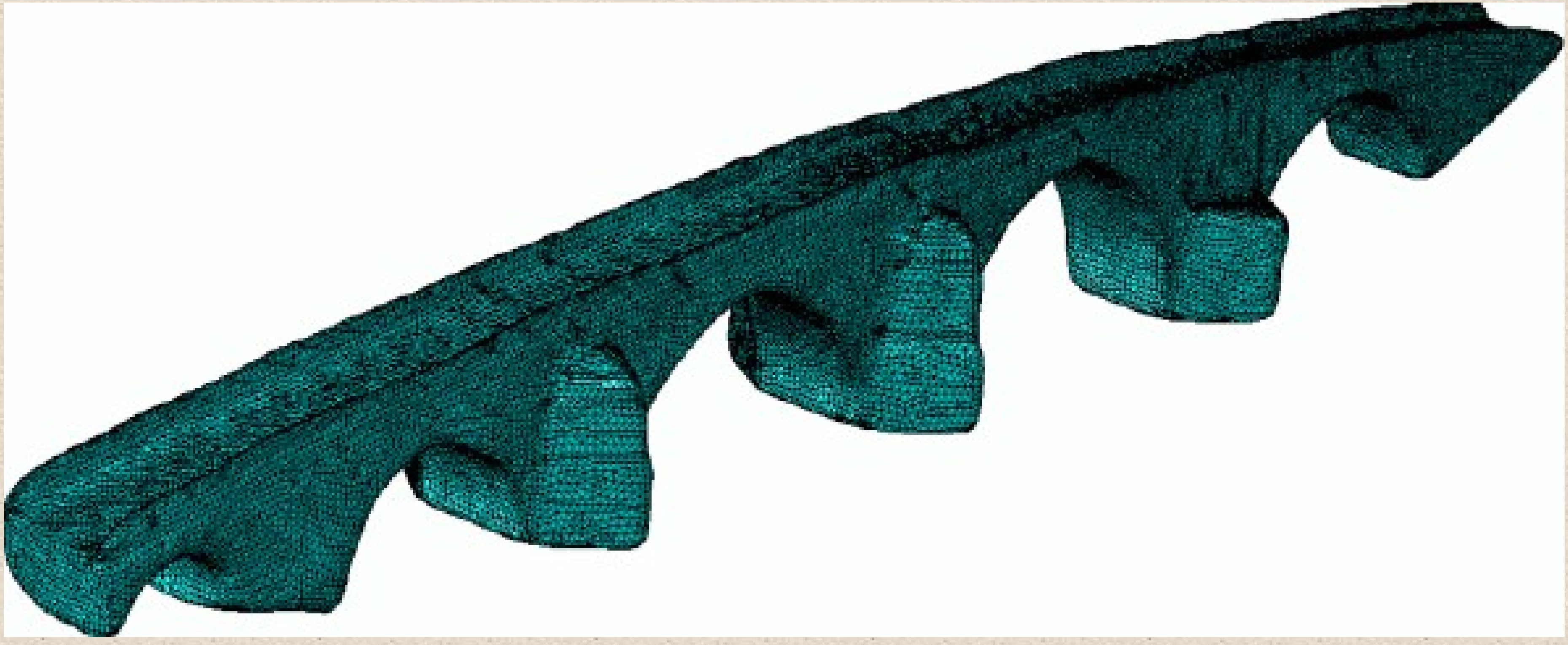




(a) Separation stress = 0.25MPa,
(b) Separation stress = 0.00MPa.

Classical 4 hinges collapse mechanism

Analysis of the whole structure

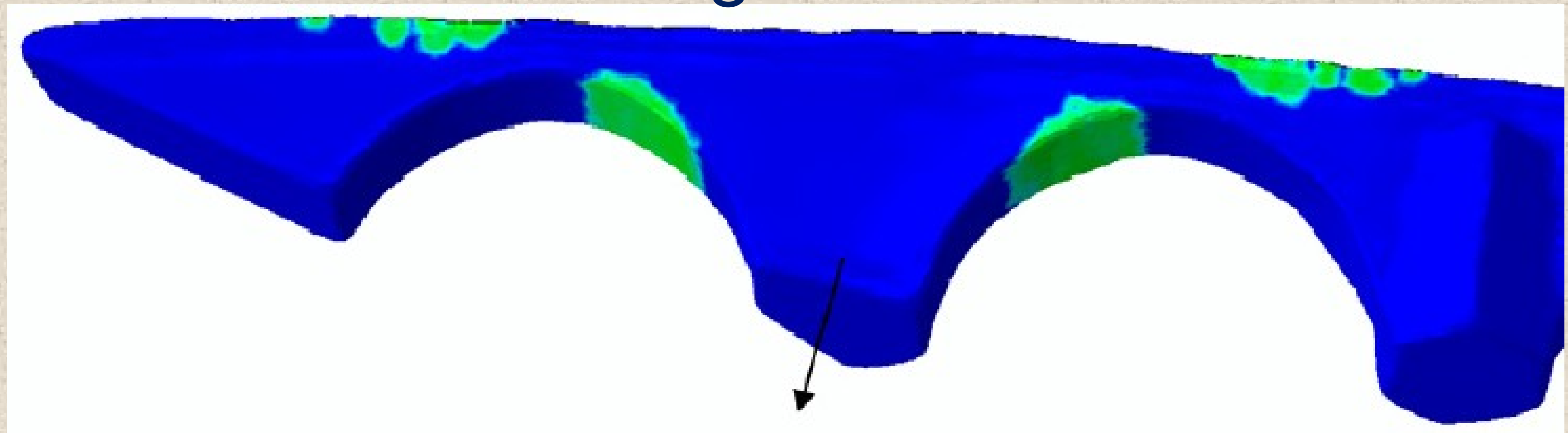


FE Mesh of the whole structure

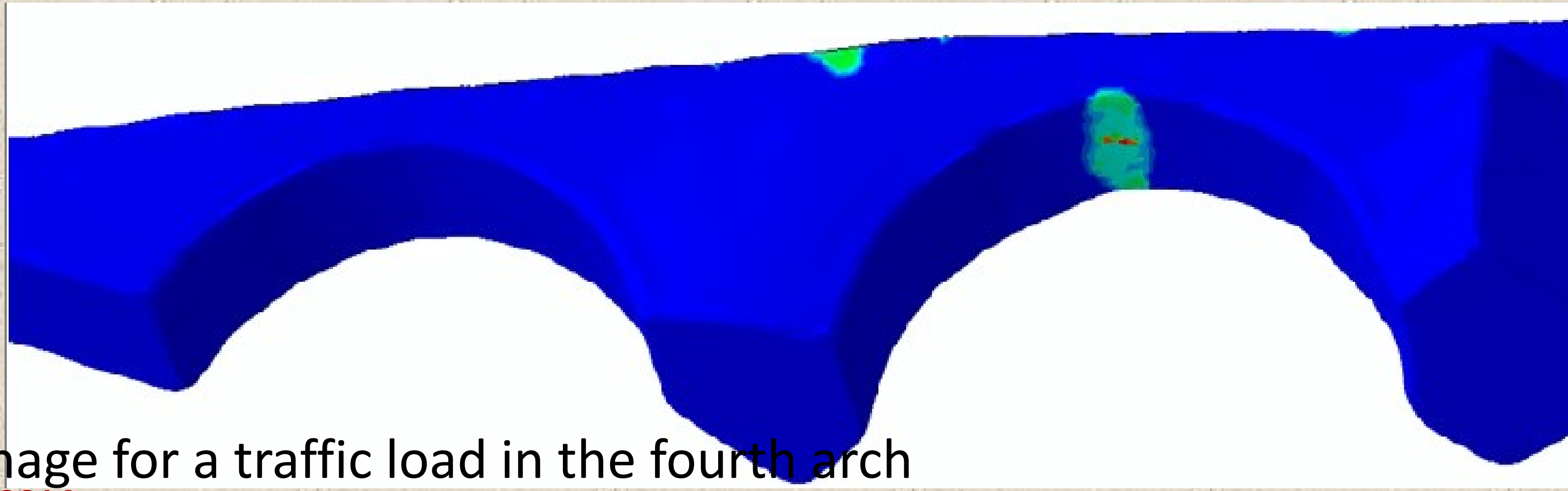
The main dimensions of the bridge are :
- Length of spans (right to left): 3.58m, 6.56m, 10.01m, 11.14m, 10.30m.
- Rise of arches (right to left): 1.79m, 3.77m, 5.22m, 5.80m, 4.75m

Results – 3d analysis

Damage model



Damage on the fourth and fifth arch for a vertical displacement of the fourth abutment.

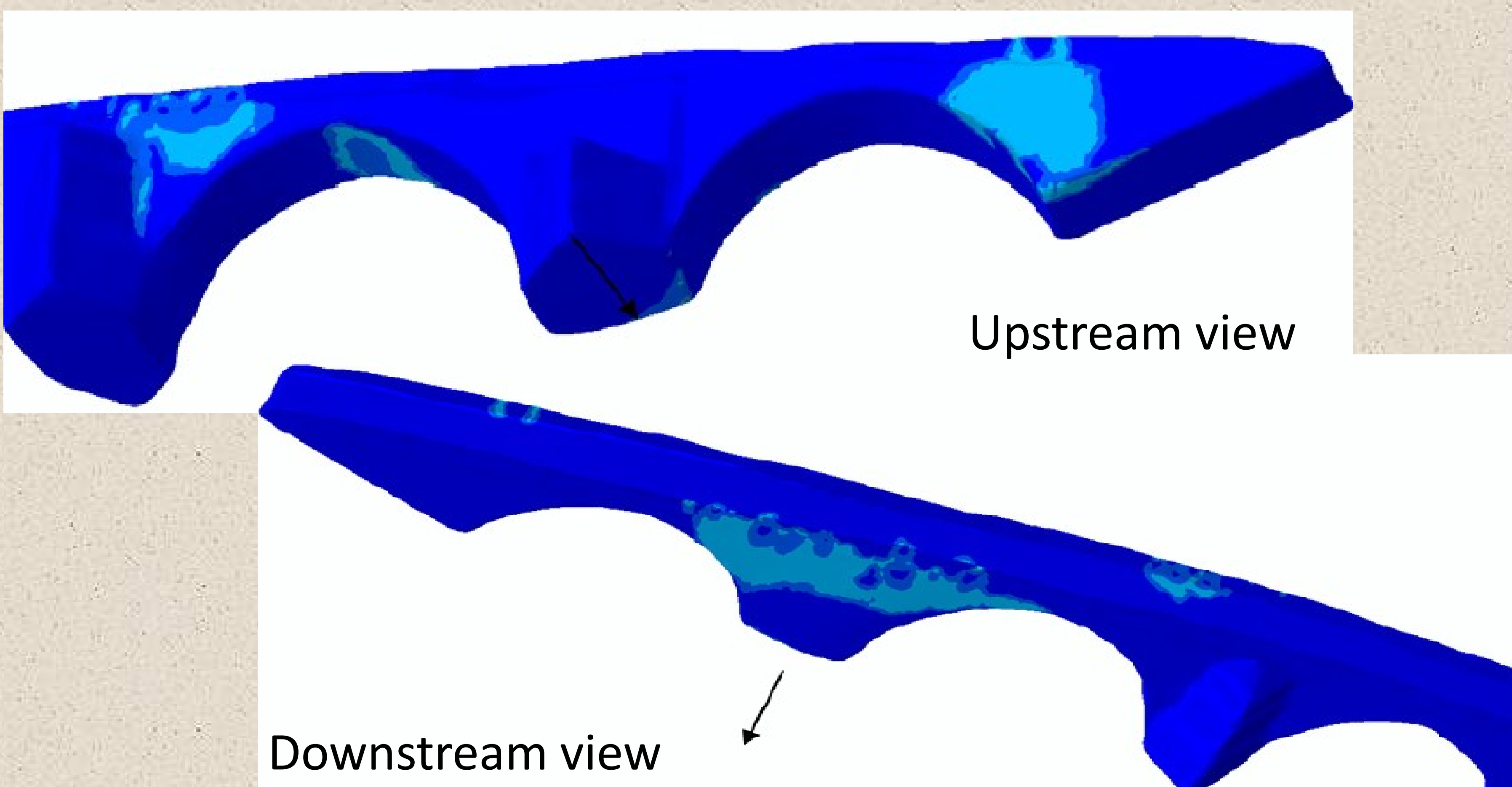


Damage for a traffic load in the fourth arch

Results – 3d analysis

Damage model

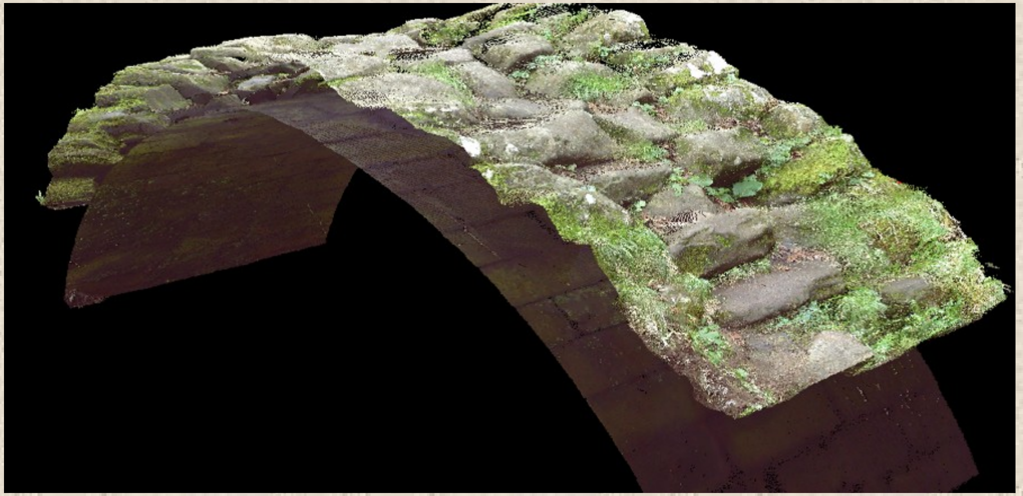
Damage for a traffic load on the fourth arch and a transverse (out of plane) movement of the fourth abutment



- Conde B., Drosopoulos G.A., Stavroulakis G.E., Riveiro B., Stavroulaki M.E. (2016), ’Inverse analysis of masonry arch bridges for damaged condition investigation: Application on Kakodiki bridge’, *Engineering Structures* 127, pp. 388-401
- Conde B., Drosopoulos G.A., Riveiro B., Stavroulaki M.E., Stavroulakis G.E. (2015), “Influence of Stones’ Size on the Collapse of Masonry Bridges”, 8th GRACM International Congress on Computational Mechanics, Volos, Greece
- Riveiro B., Conde B., Drosopoulos G.A., Stavroulakis G.E., Stavroulaki M.E. (2016), “Fully Automatic Approach for the Diagnosis of Masonry Arches from Laser Scanning Data and Inverse Finite Element Analysis”, 10th International Conference on Structural Analysis of Historical Constructions (SAHC), Leuven, Belgium
- M.E. Stavroulaki, ‘Dynamic analysis of a stone bridge including contact and friction effects’, *International Conference on Nonsmooth / Nonconvex Mechanics with Applications in Engineering (NNMAE2006),* Thessaloniki, Greece, July, 2006.

Collapse Analysis of the Xuño Bridge

Influence of the real geometry and special the stones size of the arch to the collapse mechanism.

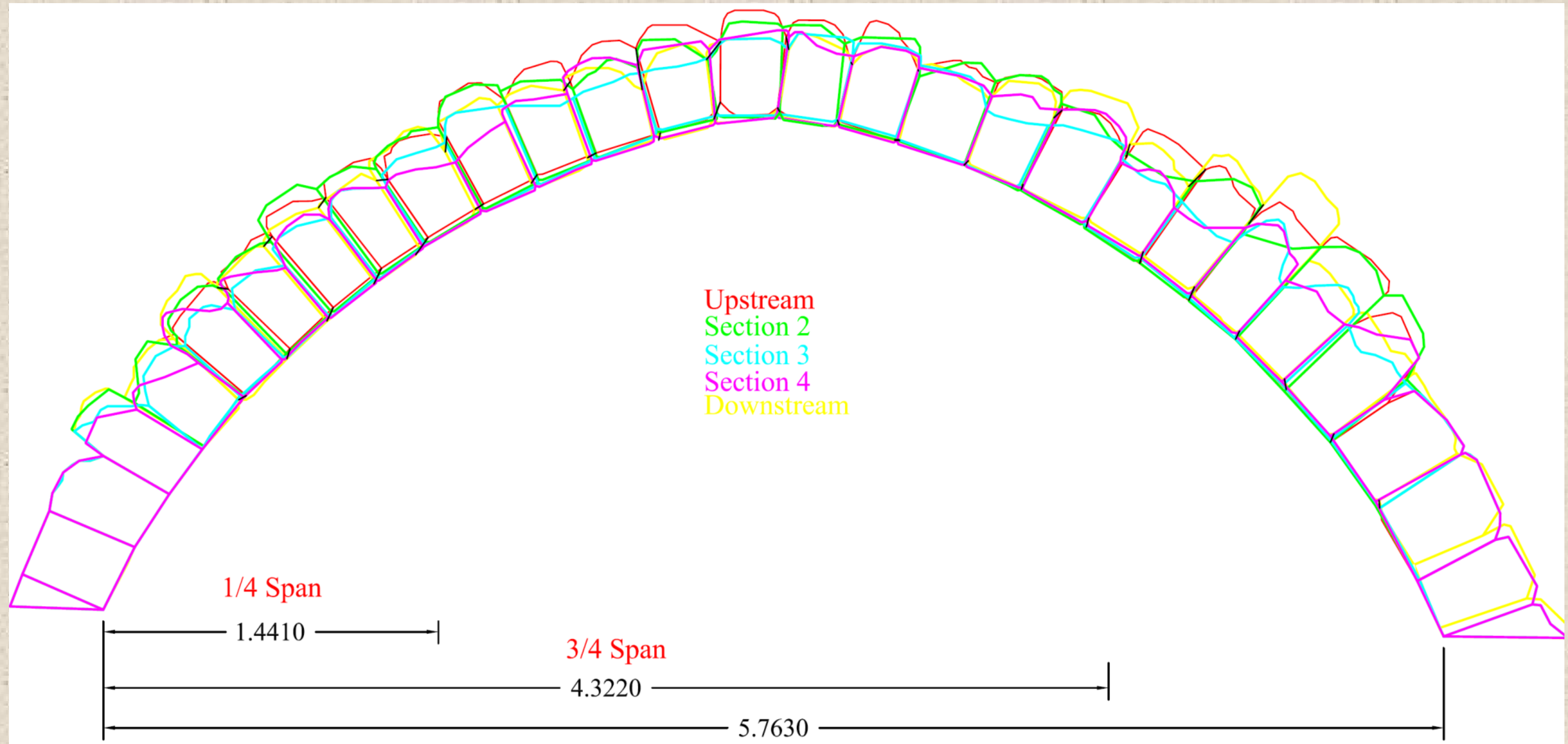


(a) 3D point cloud model showing the irregularity of stone´s thickness through the whole width of the arch

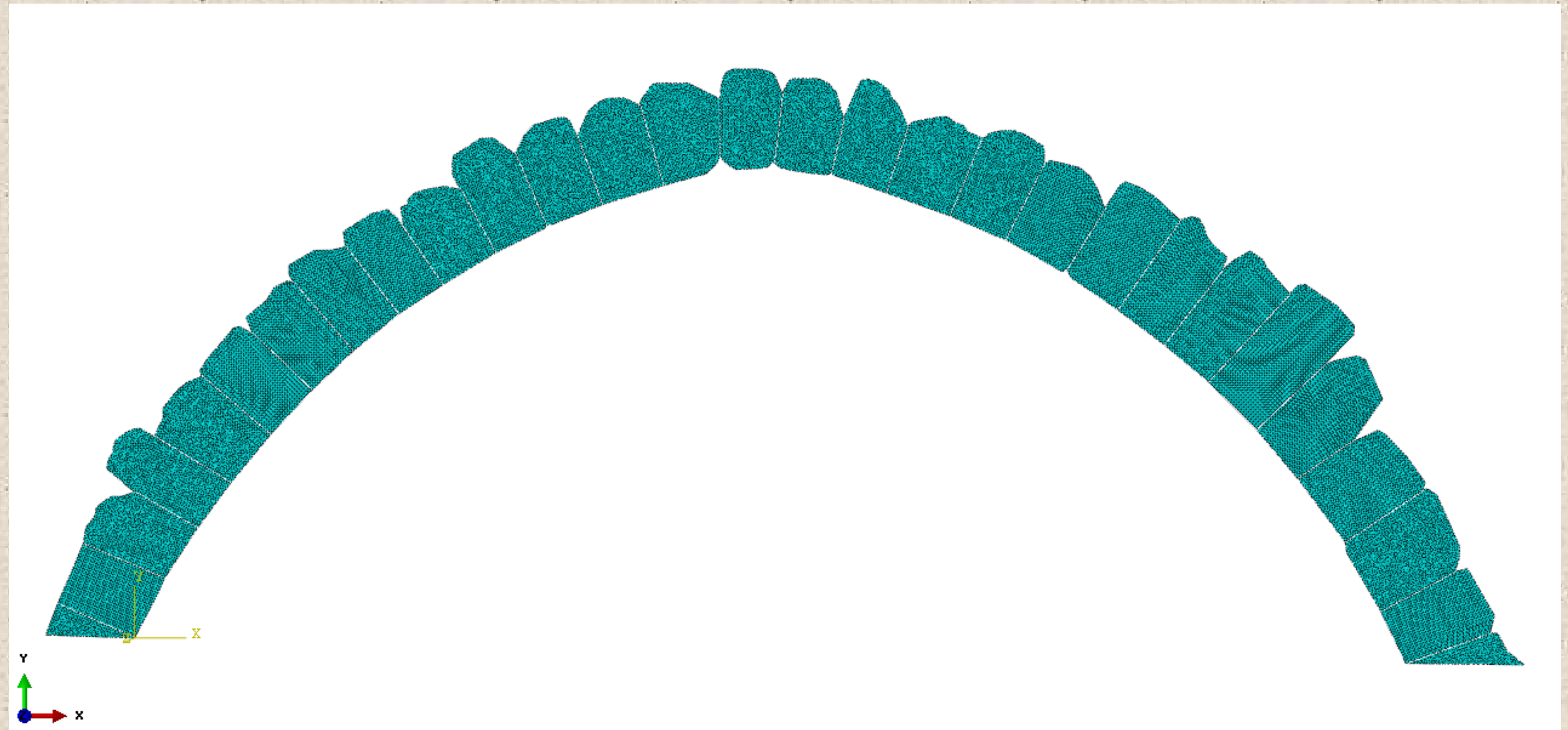
(b) Upstream view of one slice upon the arch showing diversity of the stones shapes and position of the real contact interfaces

In particular

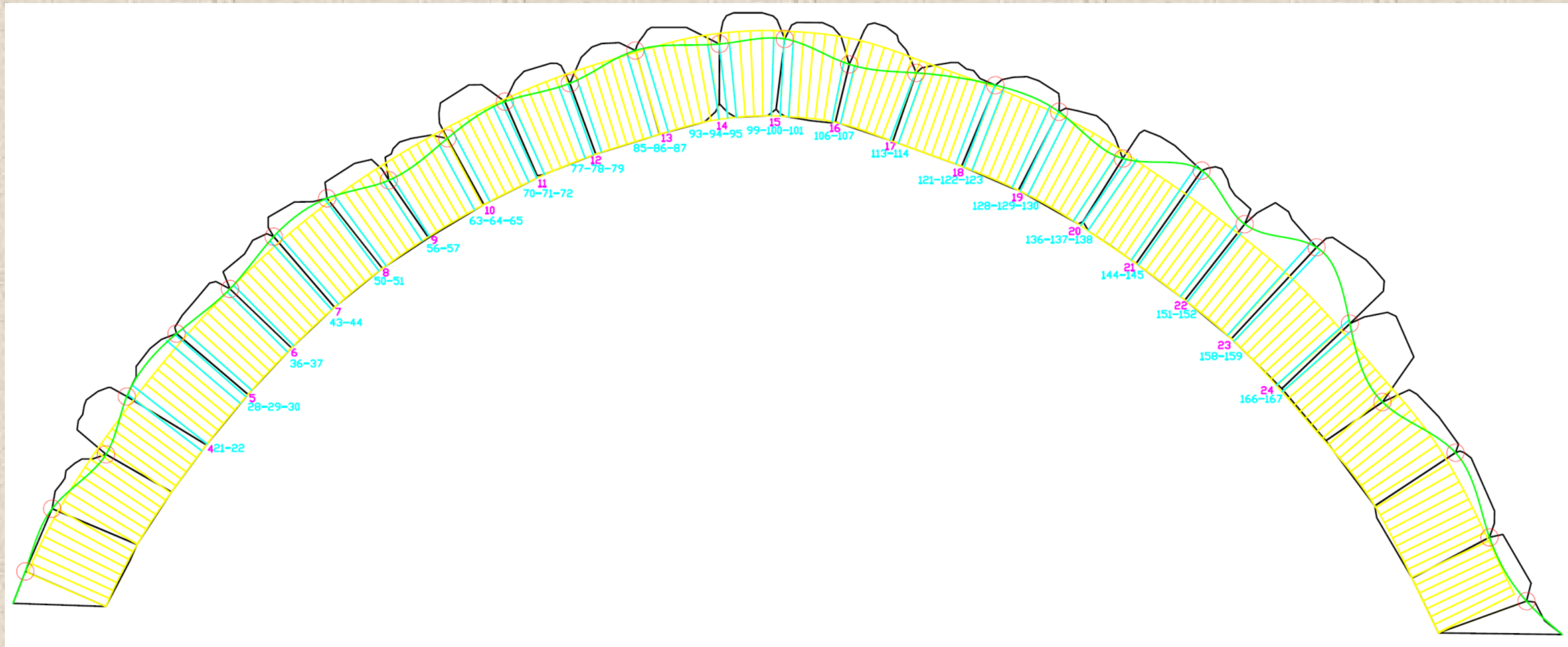
- A comparative study of various two-dimensional slices taken along the whole width of arch from Xuño Bridge.
- Five different two-dimensional models with unilateral contact interfaces have been created.
- All of these slices are separated a distance of 0.5875 m so that they cover the full width of the arch.
- Implementation of static and dynamic loading
- Comparison with the real state of the structure



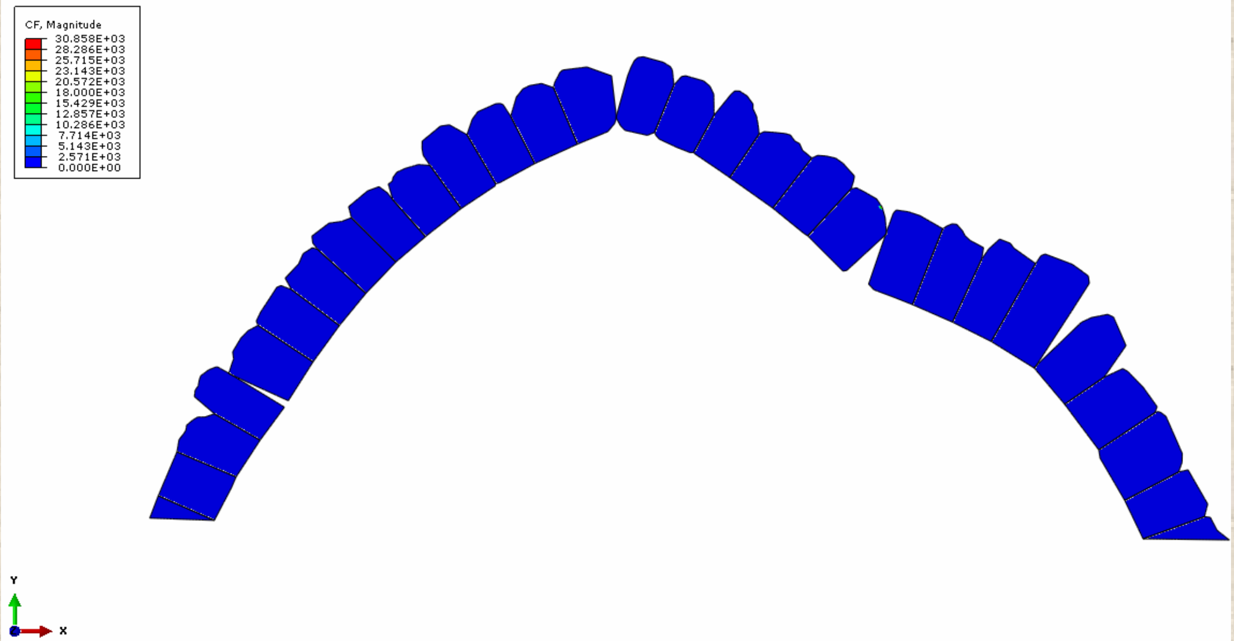
Two-dimensional model of the initial geometry at various slices along the bridge.



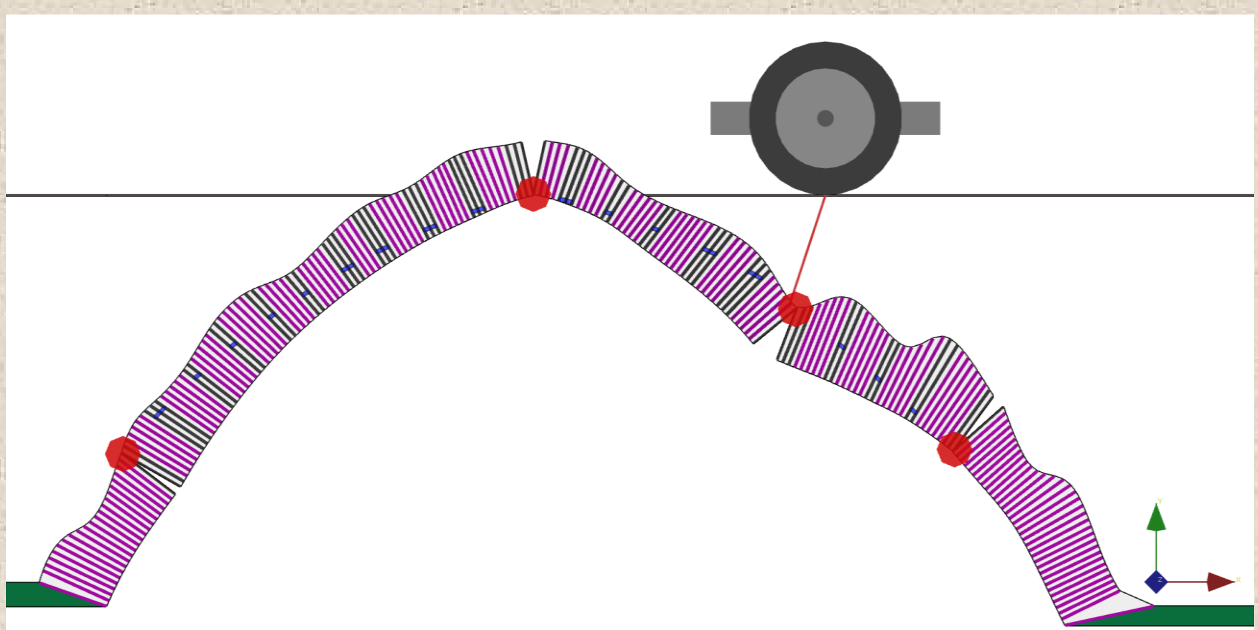
Finite element analysis models consist of quadrilateral, four-node, and plane stress elements with two translational degrees of freedom per node were analyzed in ABAQUS



Rigid block models have also been created from interfaces of real geometry and analyzed within limit analysis RING software.

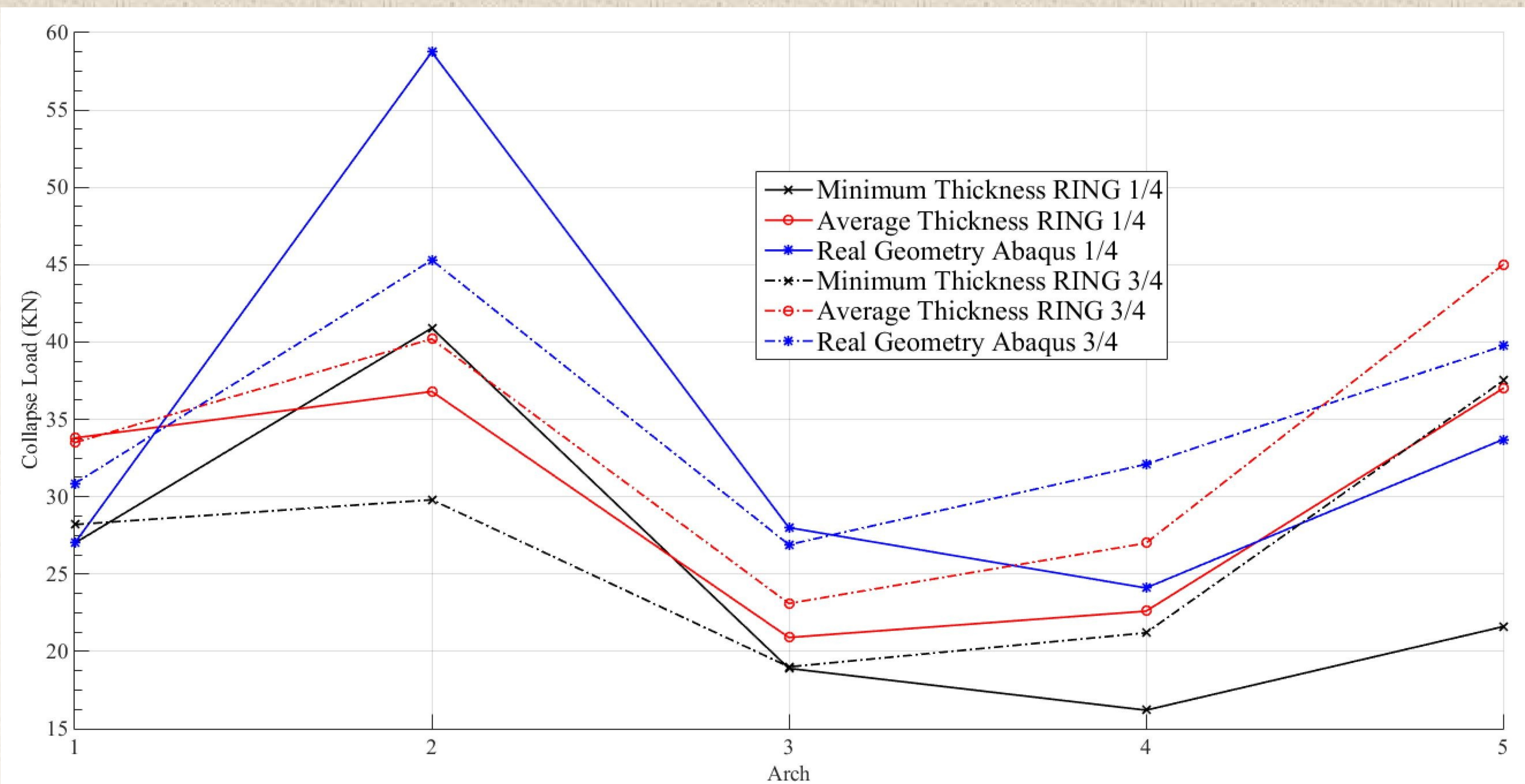


Collapse mode from FEM (failure load 30.85 kN at ¾ of the length)



Collapse mode from RING minimum thickness model (failure load 28.2 kN at ¾ of the length)

Parametric investigation



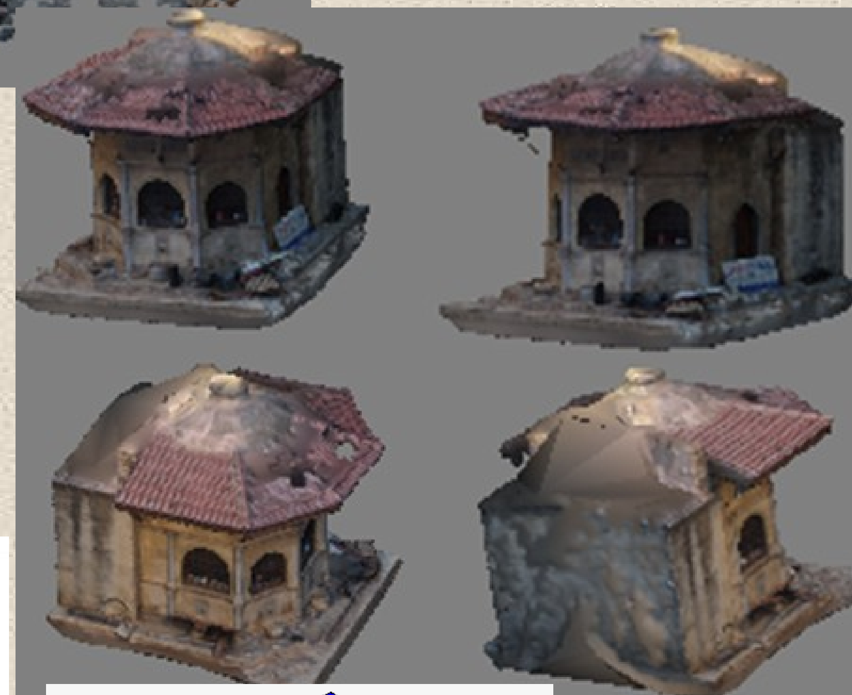
Collapse loads along the slices of the arch

PHILANTHROPIC FOUNTAIN OF KORNAROU SQUARE: USING SFM TO CALCULATE THE FOUNTAIN'S GEOMETRIC CHARACTERISTICS IN ORDER TO DETERMINE ITS INELASTIC DYNAMIC RESPONSE

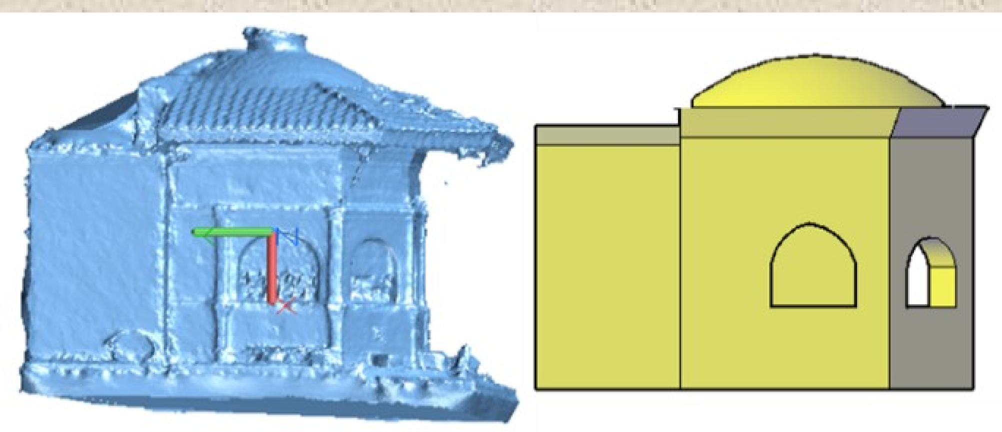
Alexandros Lyratzakis, Panagiotis Parthenios, Maria Stavroulaki (2016) 'PHILANTHROPIC FOUNTAIN OF KORNAROU SQUARE: USING SFM TO CALCULATE THE FOUNTAIN'S GEOMETRIC CHARACTERISTICS IN ORDER TO DETERMINE ITS INELASTIC DYNAMIC RESPONSE ' , Proceedings of the 8th International Congress on Archaeology, Computer Graphics, Cultural Heritage and Innovation 'ARQUEOLÓGICA 2.0' in Valencia (Spain), Sept. 5 – 7, 2016

- Use of Structure from Motion (SfM) techniques to survey inaccessible monument structures
- Application on capturing Kornarou Square's philanthropic fountain in Heraklion, Crete.
- A series of aerial and terrestrial photos of the fountain were combined in order to build the 3D geometry of the monument using Agistoft's Photoscan.
- This 3D model was used to study the dynamic behavior of the fountain.
- Its response was determined through multiple inelastic dynamic analyses. The analysis results were summarized in the average dynamic curve.

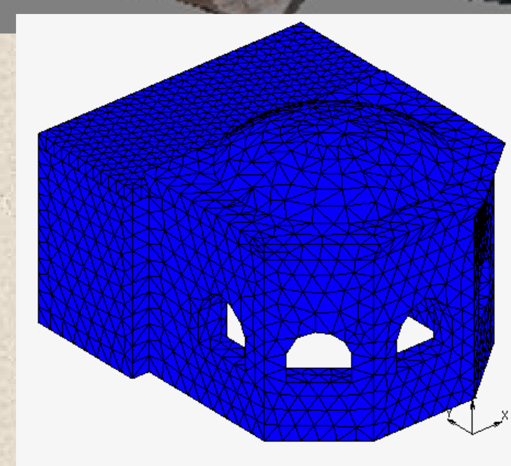
1.Dense cloud.



2. Final Agisoft Model.



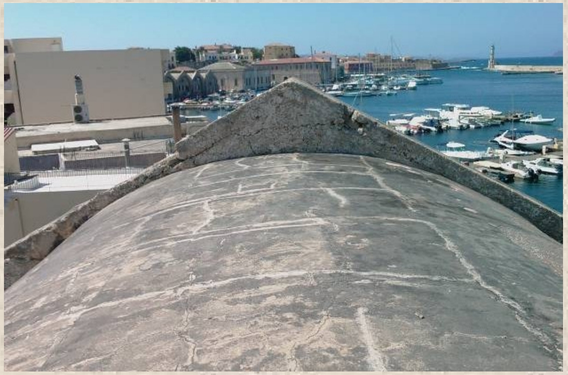
3. Left: Agisoft's mesh Right: Solid model.



4. FE Model (MSC Marc).

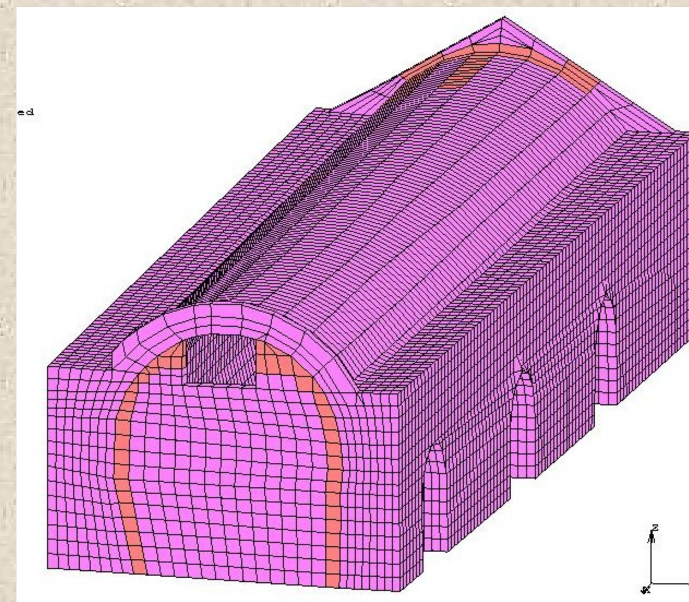
Analysis of Historical Structures with barrel vaults.

- Barrel vault is called a cylindrical surface which is as if an arch extended laterally.
- In single curve vaulted surfaces, the principle stresses along the curve will always be compressive and the inclined thrusts at the edge require enough mass of supporting system.

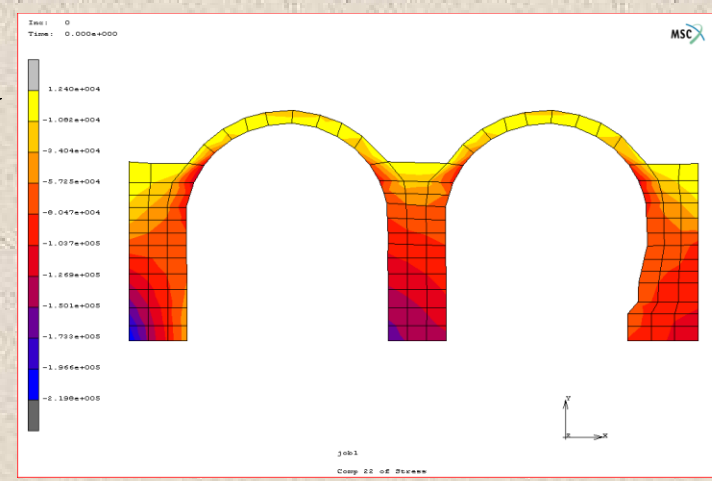


Maria E. Stavroulaki and Theodoros Tsinarakis, “Finite element analysis of masonry barrel vaults”, 7th GRACM International Congress on Computational Mechanics, Athens, 30 June – 2 July 2011

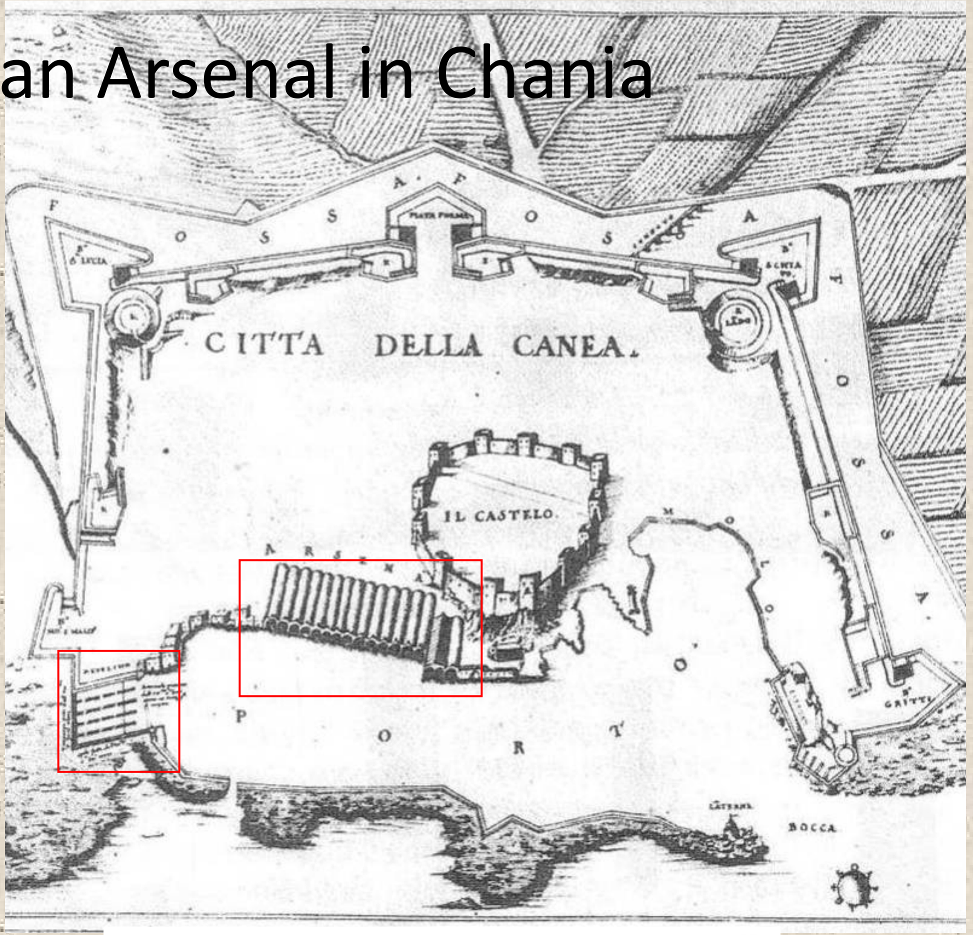
Analysis of Historical Structures with barrel vaults.



- The major simplification that is usually made is supposed to reduce the vault to a series of adjacent arches without transversal connection.
- Therefore, this model is unable to properly simulate the three dimensional effects of the vault.
- Moreover, the structural role of the spandrels has always been neglected, while, it is well known that they stabilise the vaults.



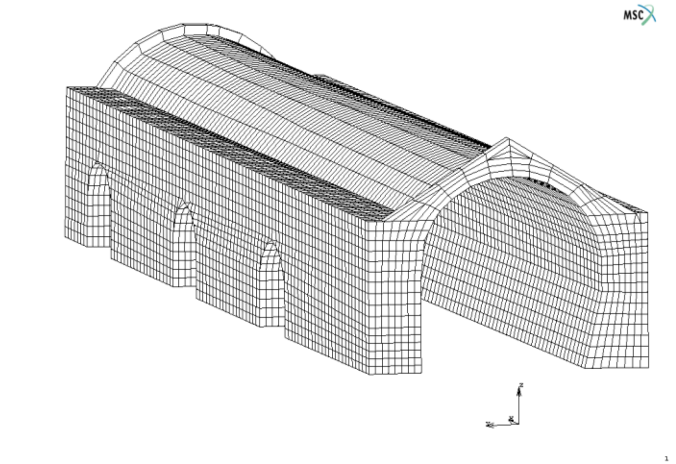
Case study: A Venetian Arsenal in Chania



- First Arsenal Complex (1467-1599)
  - ➔17 facing north

- Second Arsenal Complex (1600-1636)
  - ➔5 facing west
  - ➔only 2 fully complete by local official "Benedetto Moro" between 1612-1614

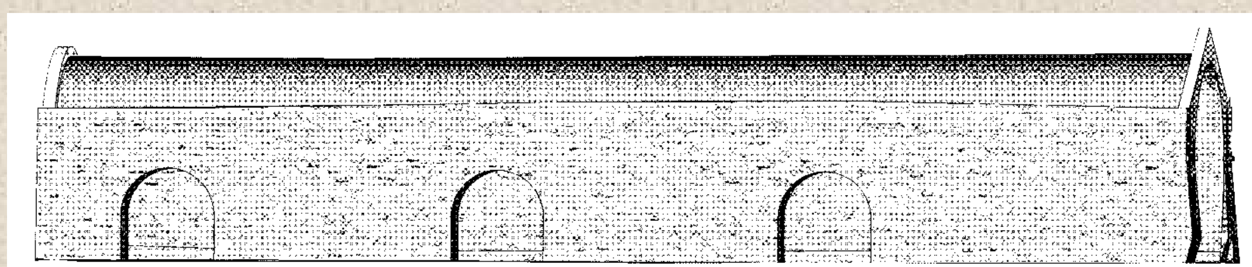
- Length 50m, Width 9m, Height 10m *in average*
- Longitudinal walls (thickness 2.5-3.0m) with numerous arched openings

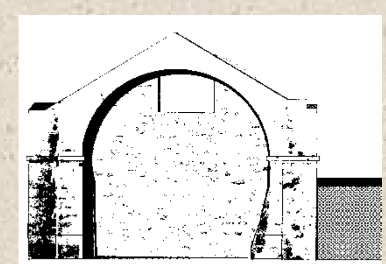


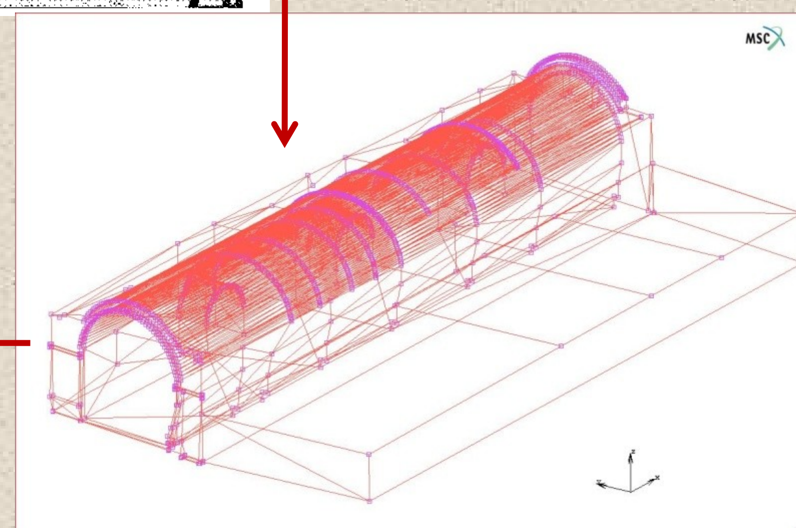
Case study: A Venetian Arsenal in Chania

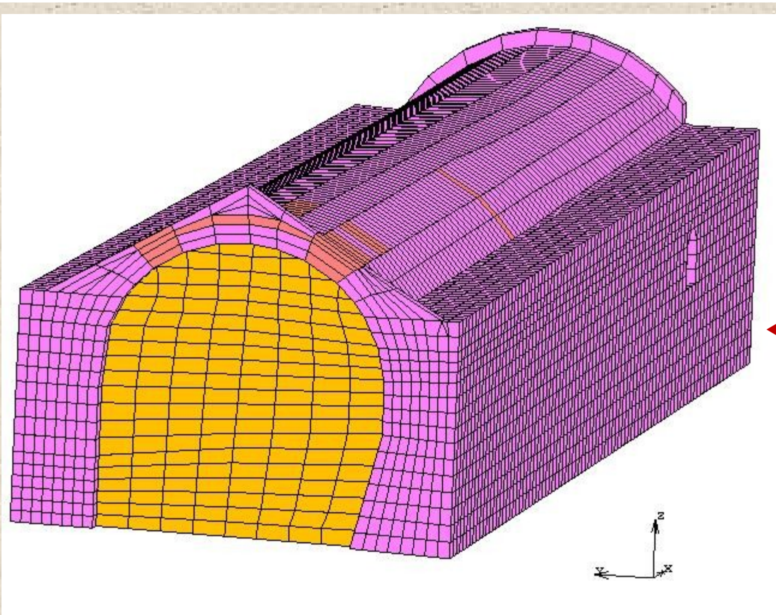
3D Finite element model,

Incorporating the structure's geometry into the FEM model



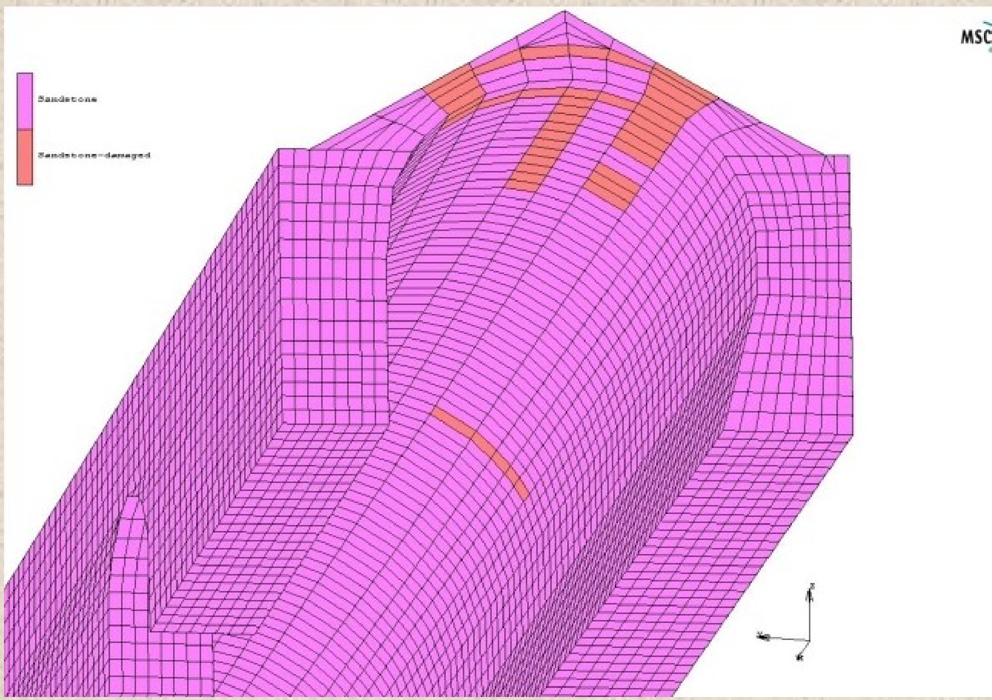






Present condition of the examined Arsenal

- Numerous visible damages on the **barrel vault** and the transverse walls

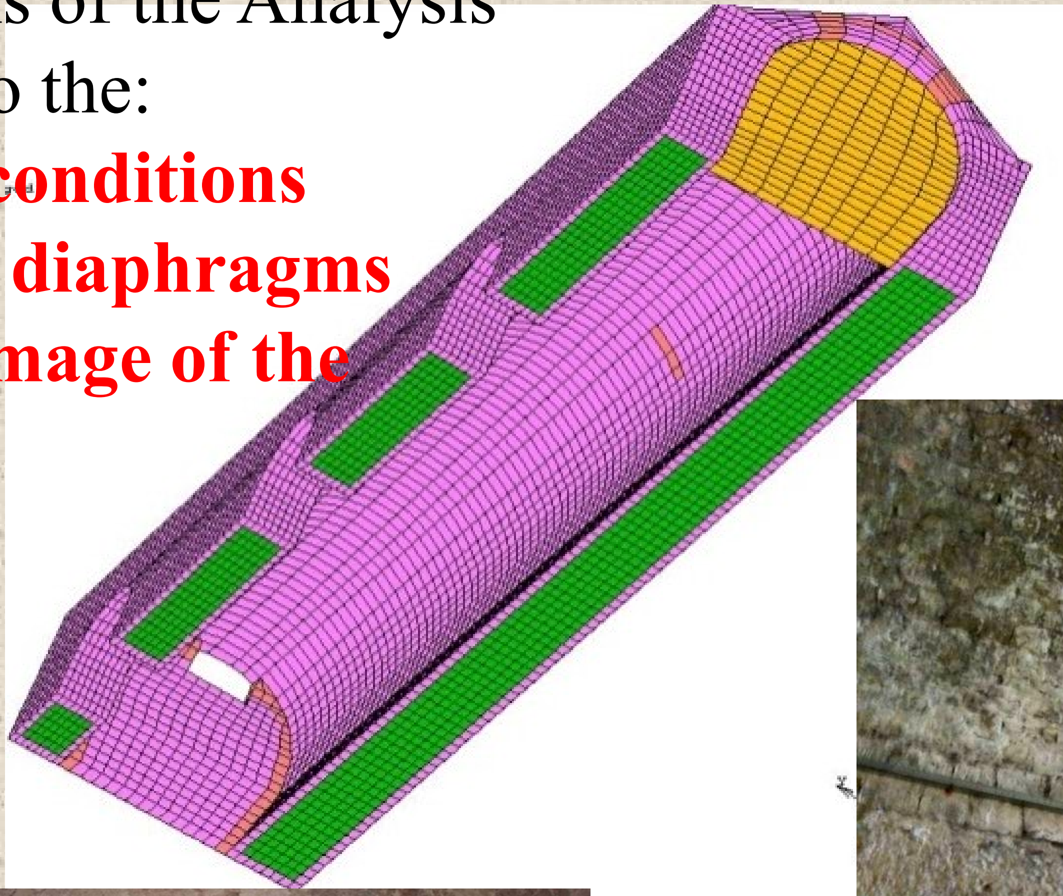


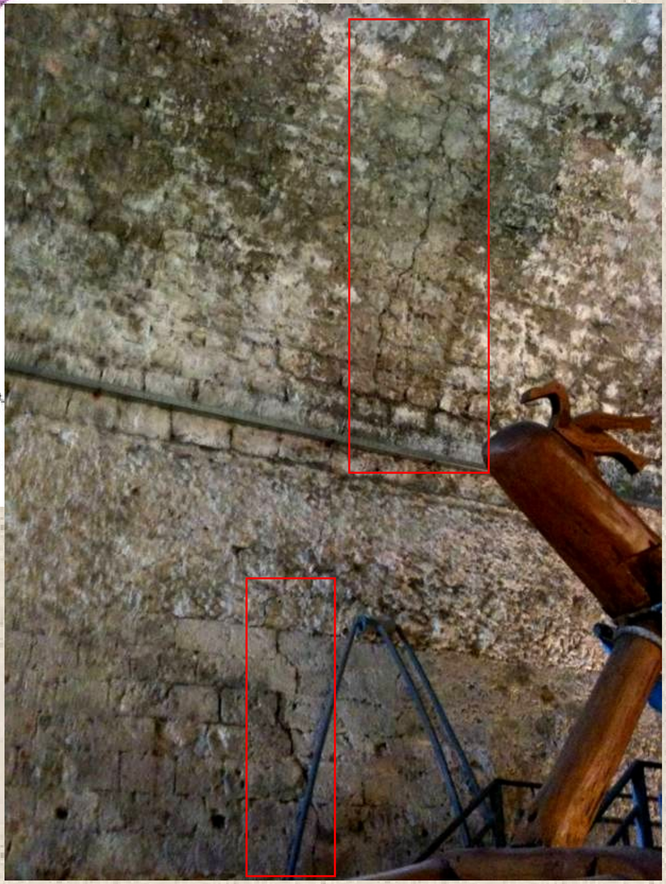
Assumptions of the Analysis in relation to the:

Boundary conditions

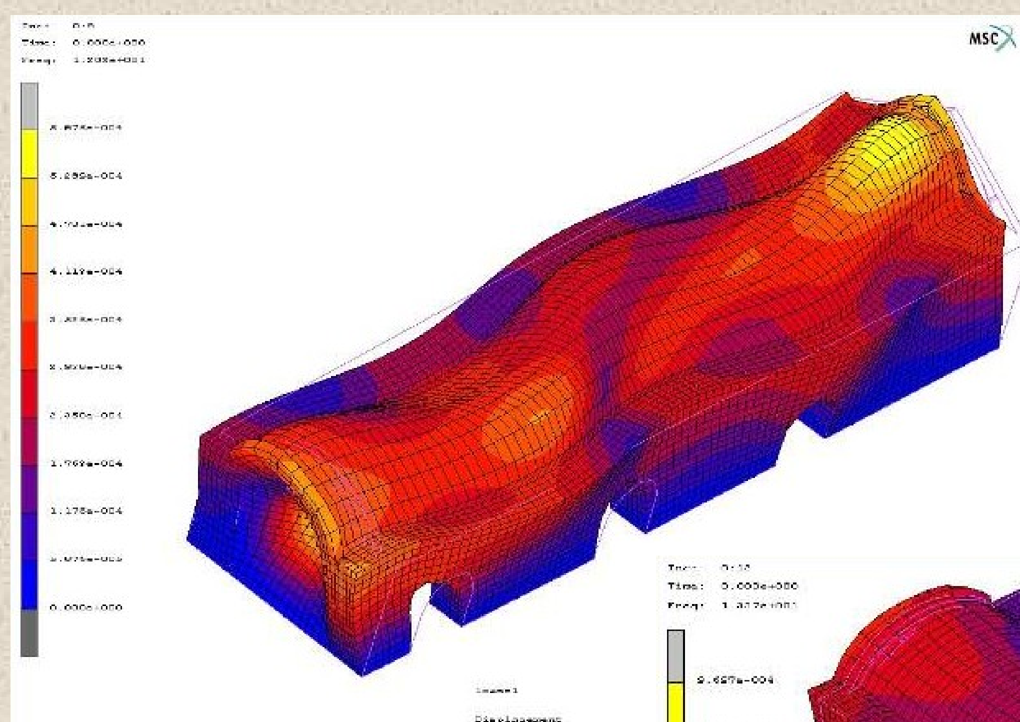
Transverse diaphragms

Quality/damage of the materials

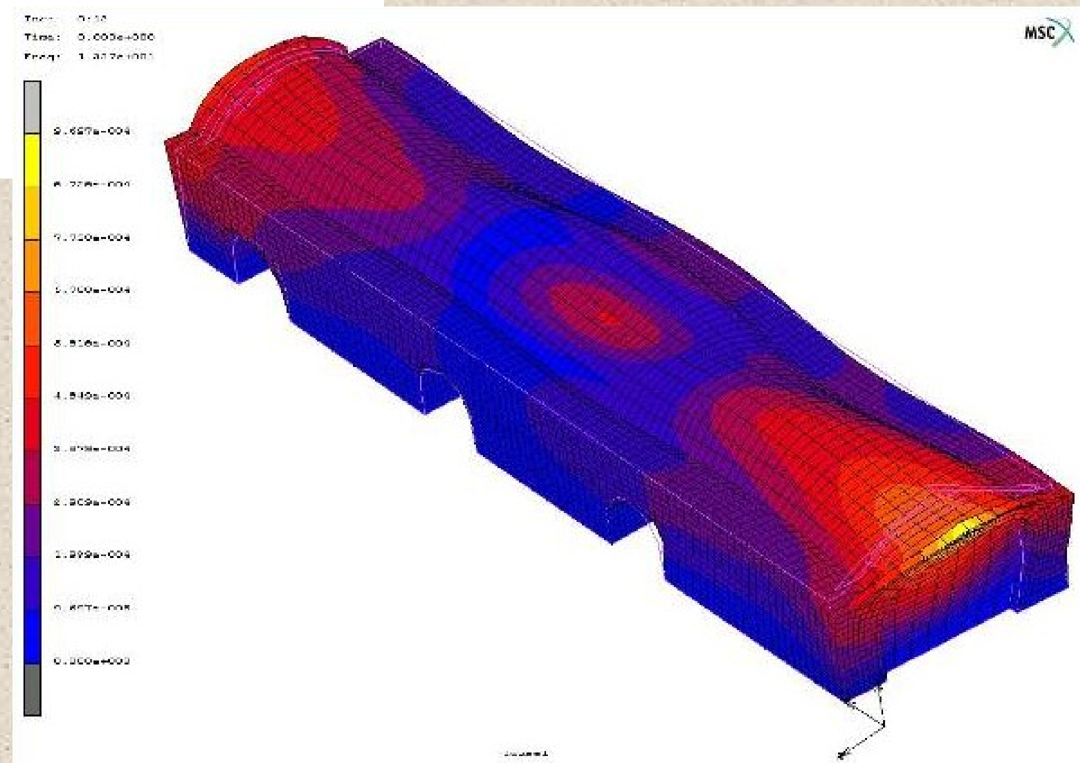




Dynamic modal analysis



Mode 12



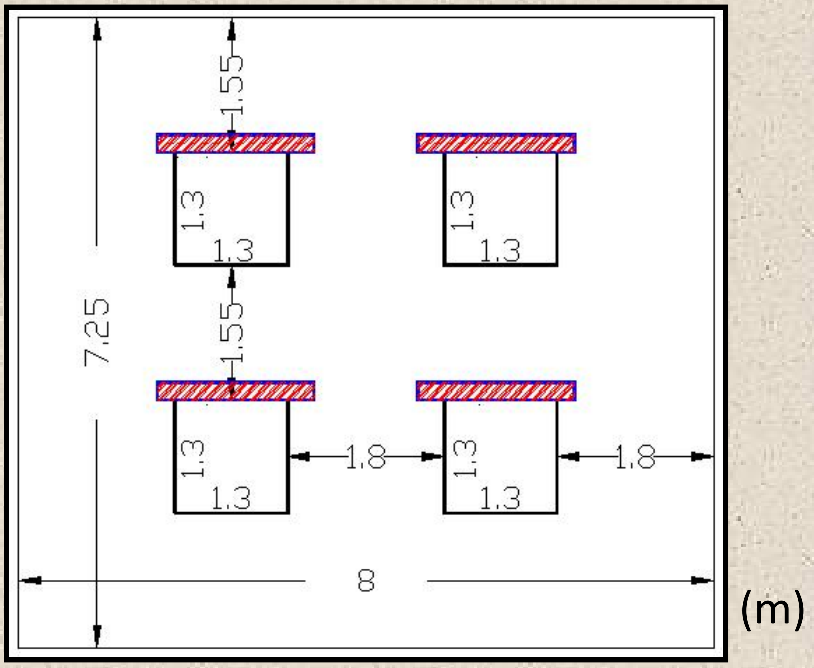
Mode 9

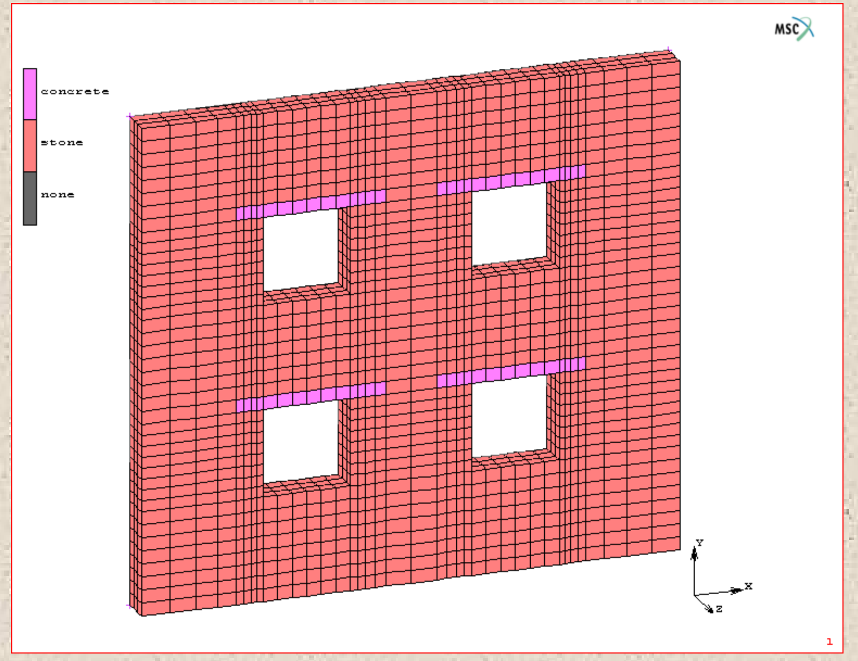
Correlation with in situ measurements of the dynamic characteristics

Structural analysis of existing structures

- Influence of strengthening techniques
- Evaluation of the structure’s condition after the proposed restorations

Dynamic analysis of a masonry wall with reinforced lintels or tie beams





•Maria E. Stavroulaki, Vagelis B. Liarakos (2012), 'Dynamic analysis of a masonry wall with reinforced lintels or tie beams', Engineering Structures, Elsevier, 44, pp. 23-33.

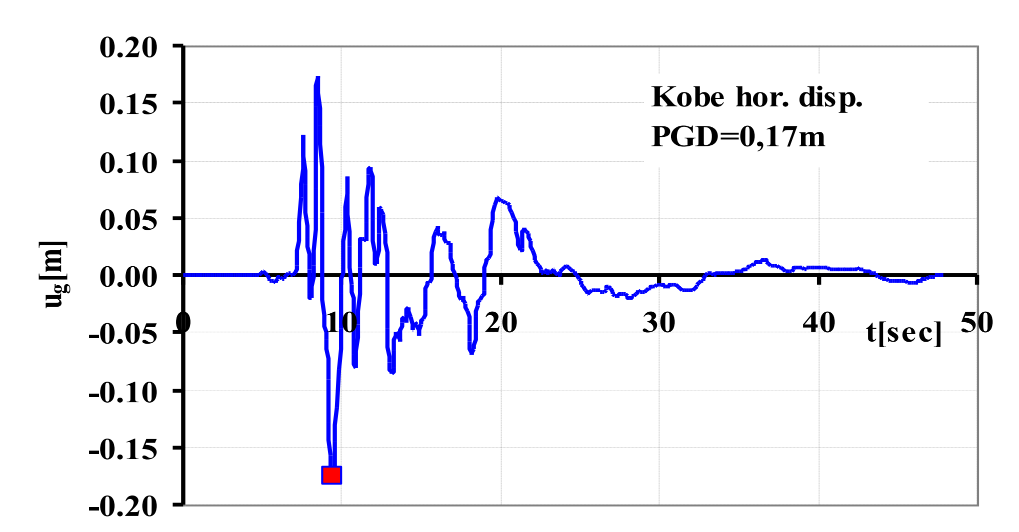
•M. E. Stavroulaki, G.E. Stavroulakis (2002), "Unilateral contact applications using FEM software", 'Invited paper' in *International Journal of Applied Mathematics and Computer Sciences, Special Issue: Mathematical Modeling and Numerical analysis in Solid Mechanics*, Guest Editors: M. Sofonea, J.M. Viano, 12(1).

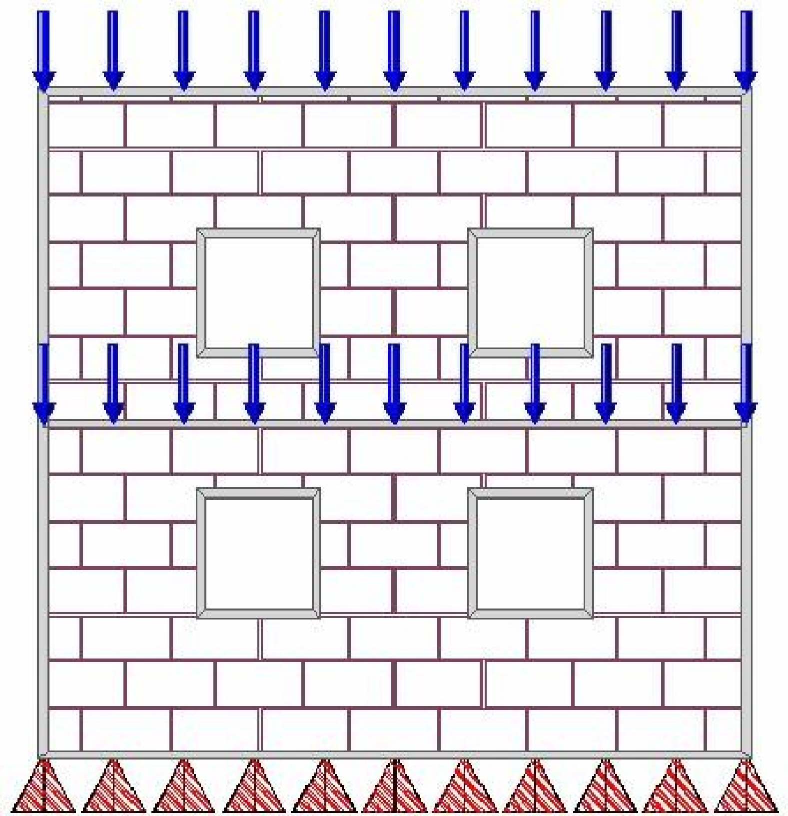
•Maria E. Stavroulaki, Vagelis B.Liarakos, 'Parametric dynamic analysis of a masonry wall with lintels of reinforced concrete over the openings', *ECCOMAS Thematic Conference on Computational Methods in Structural Dynamic and Earthquake Engineering*, Rethymno, Crete, Greece, June, 2007.

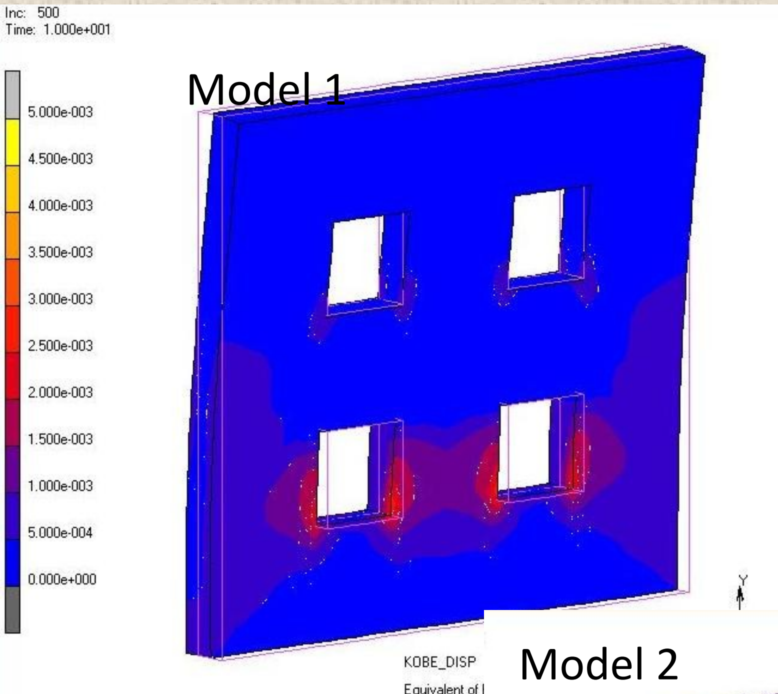
Finite Element Modeling

Loads

- the weight of the mass,
- a vertical pressure at the level of the first floor (loads from the horizontal slab),
- a vertical pressure at the top level (loads of the roof) and
- a displacement history according to the earthquake of Kobe (1996) at the base of the wall (fig. 2) in the out of plane direction (perpendicular to the wall).



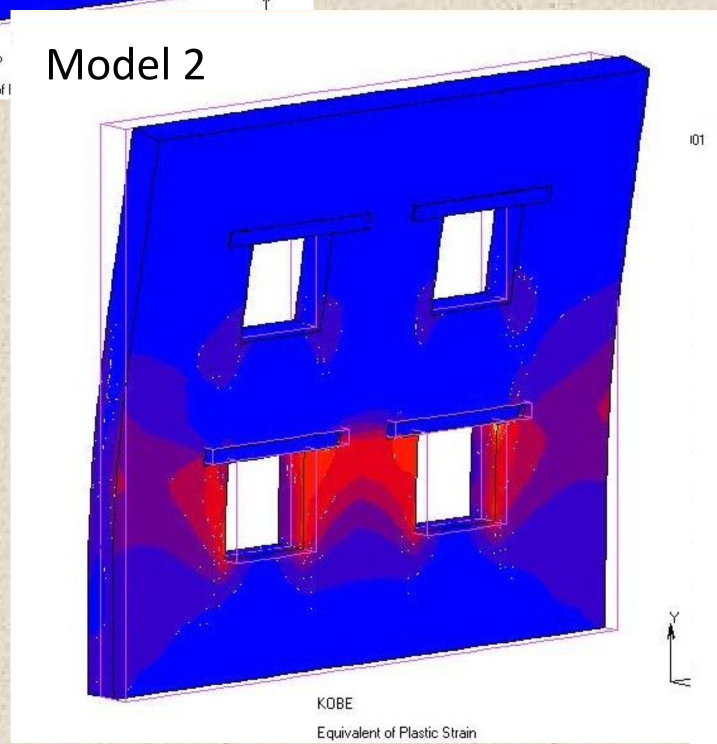


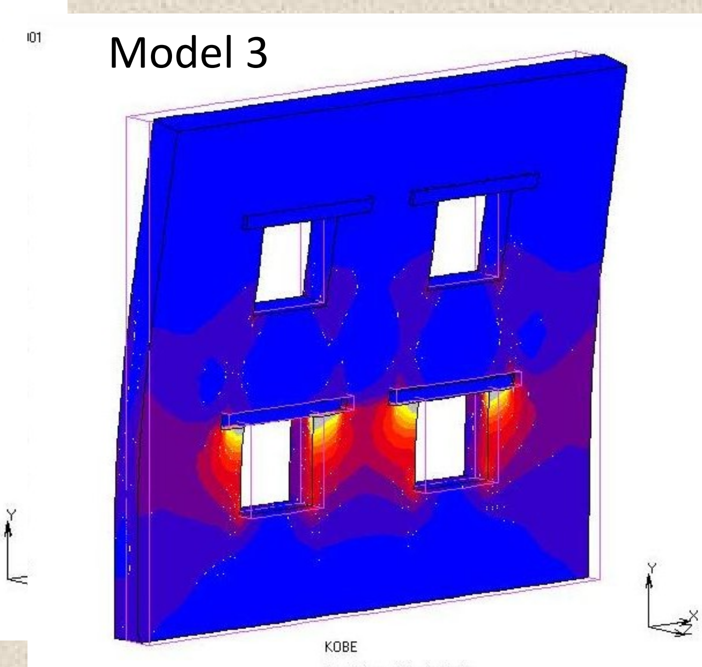


The estimation of the region with plastic strain is an indication of failure and crack development.

Strong excitation, low duration

INCREASE OF PLASTIC STRAINS



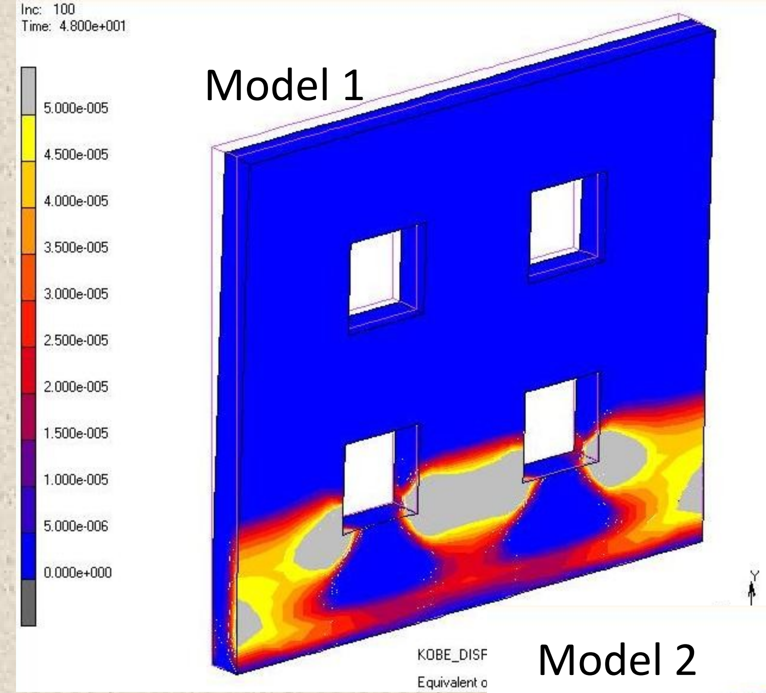


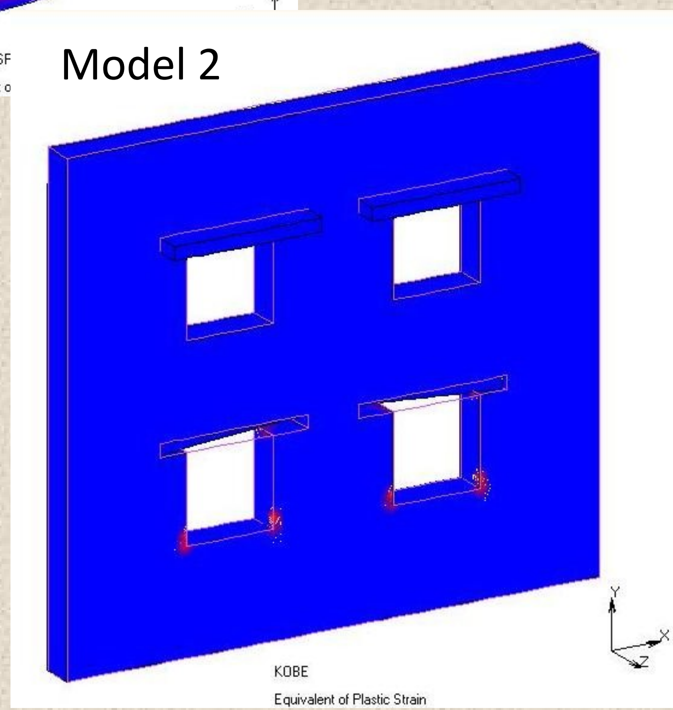
***Model 1*: Fixed conditions between the masonry wall and the lintels.**

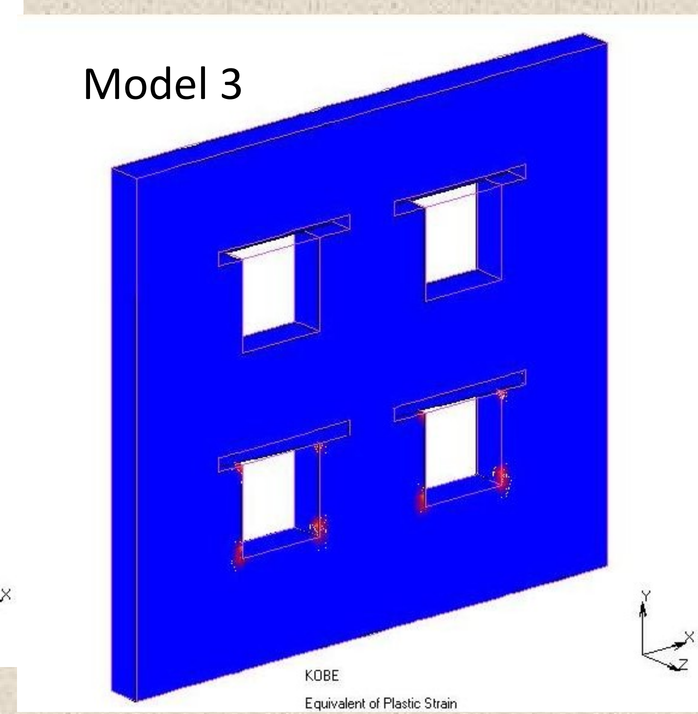
Contact conditions with friction coefficient equal to: 0.4 (*Model 2) and* 0.6 (*Model 3)*

Non strong excitation, high duration

ELIMINATION OF PLASTIC STRAINS



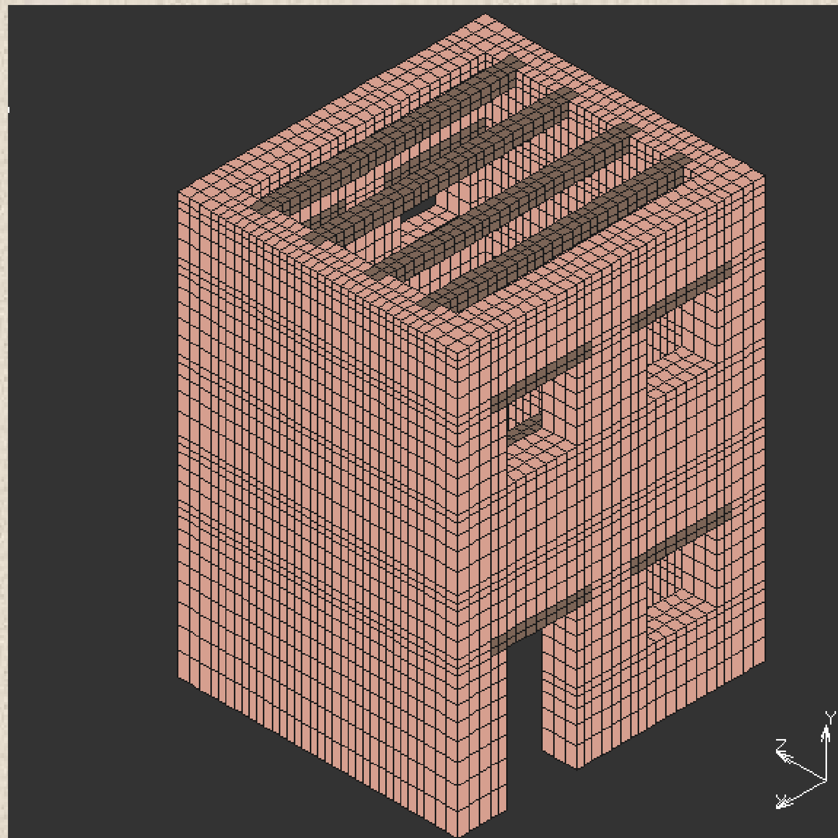


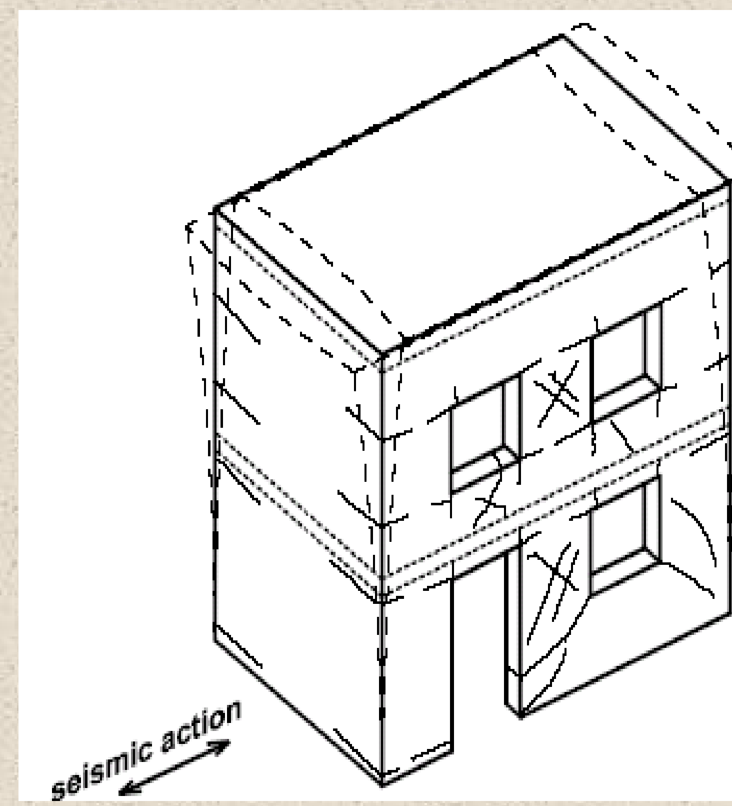


***Model 1*: Fixed conditions between the masonry wall and the lintels.**

Contact conditions with friction coefficient equal to: 0.4 (*Model 2) and* 0.6 (*Model 3)*

Seismic behavior of an unreinforced masonry building with various floor systems



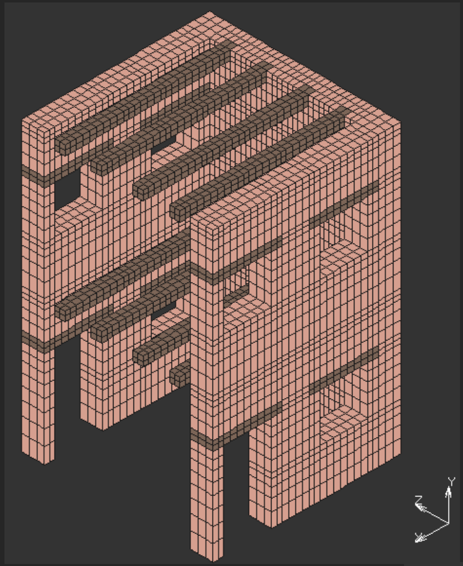


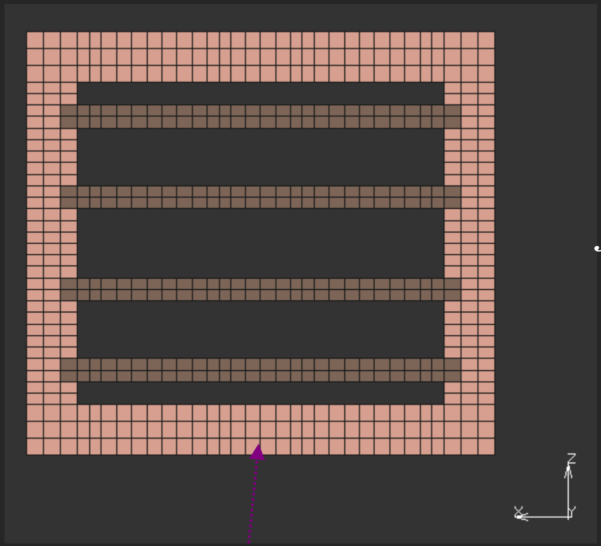
M. E. Stavroulaki, Ch. K. Amanatidou, 'Seismic behavior of an unreinforced masonry building with various floor systems', *Proceedings of the Ninth International Conference on Computational Structures Technology,* Athens, Greece, September, 2008.

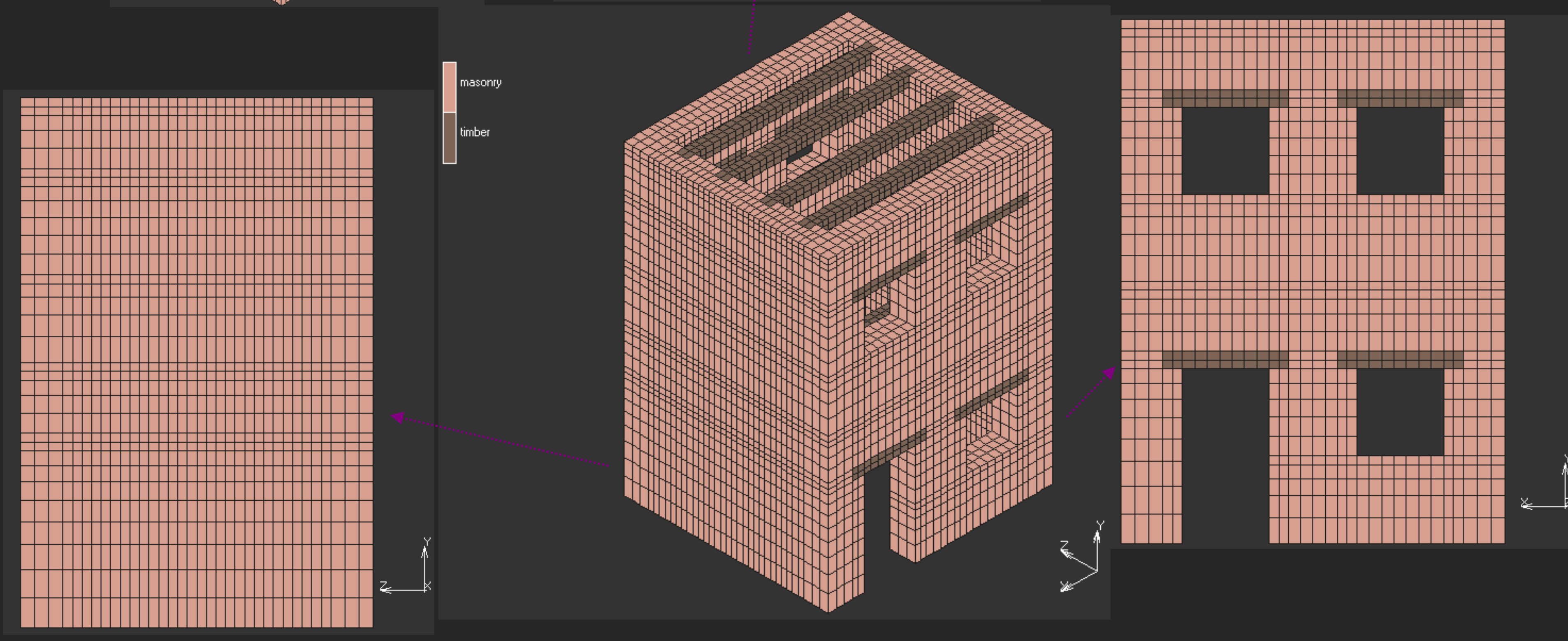
MODEL 1, *wooden floors*

17480 nodes

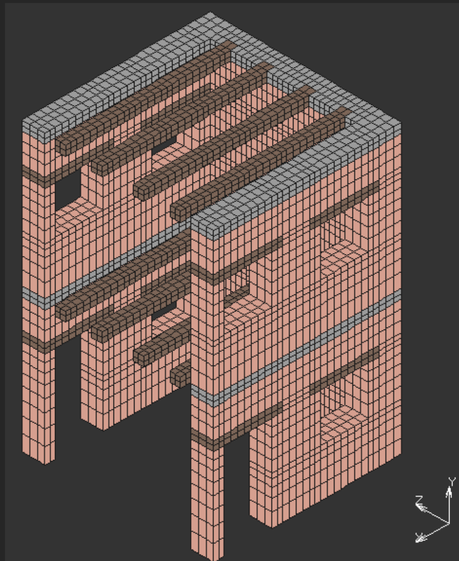
11854 solid elements

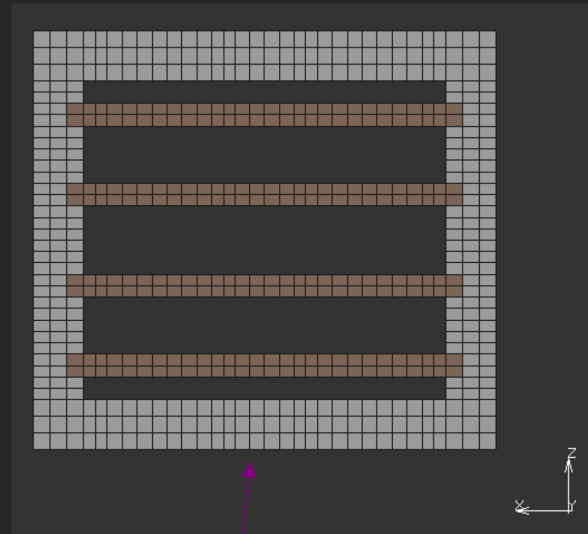


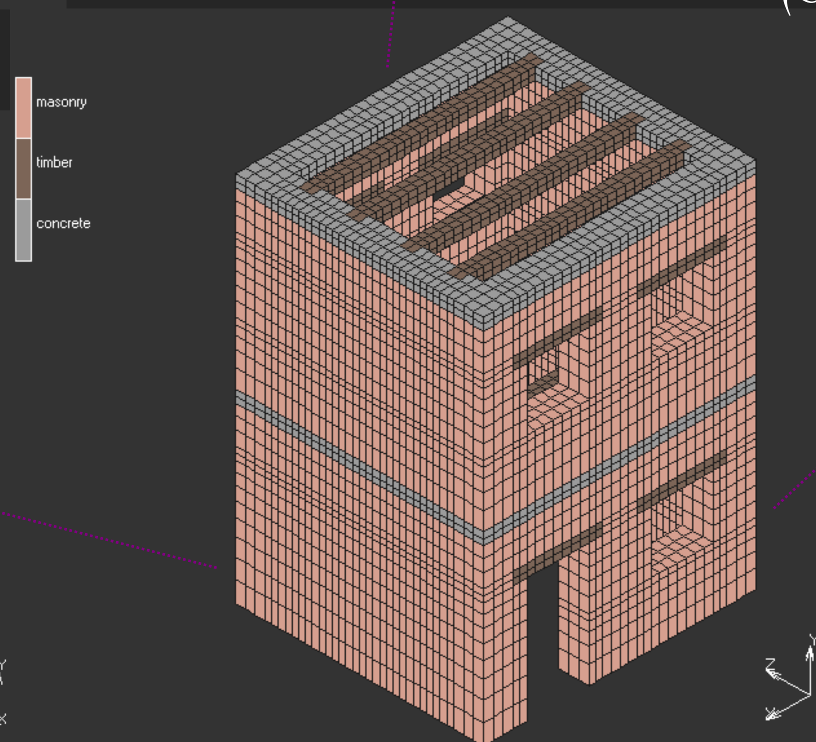


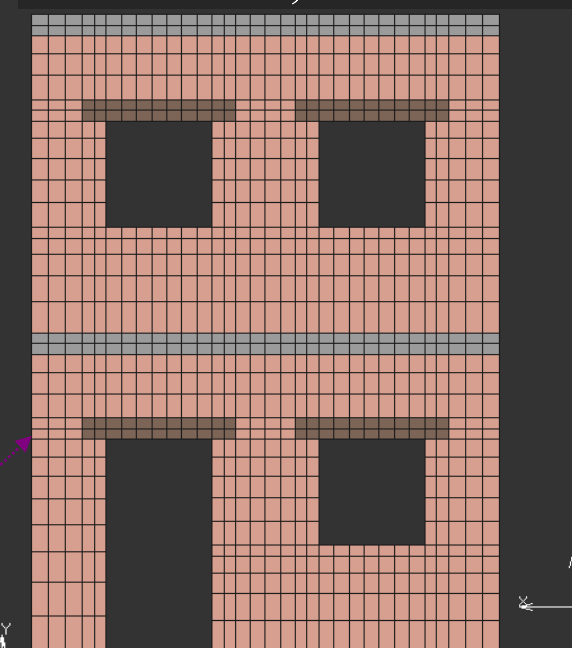


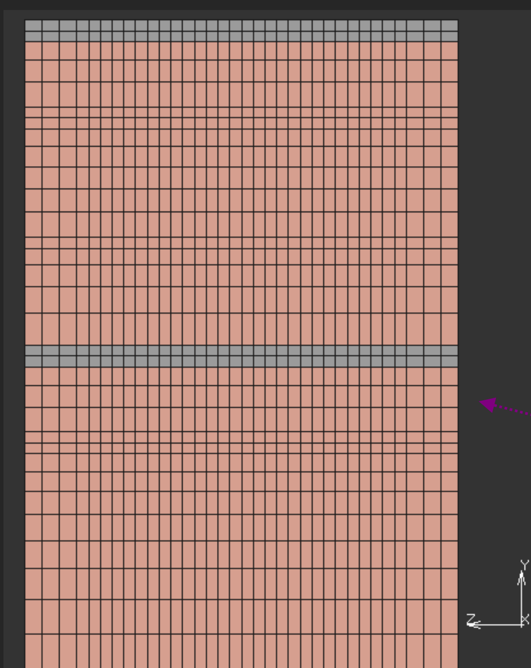
MODEL 2, *wooden floors and horizontal reinforced concrete beams at floors levels (bond beams)*







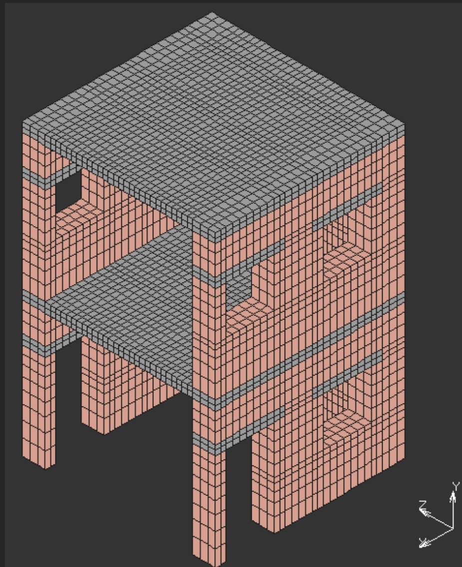


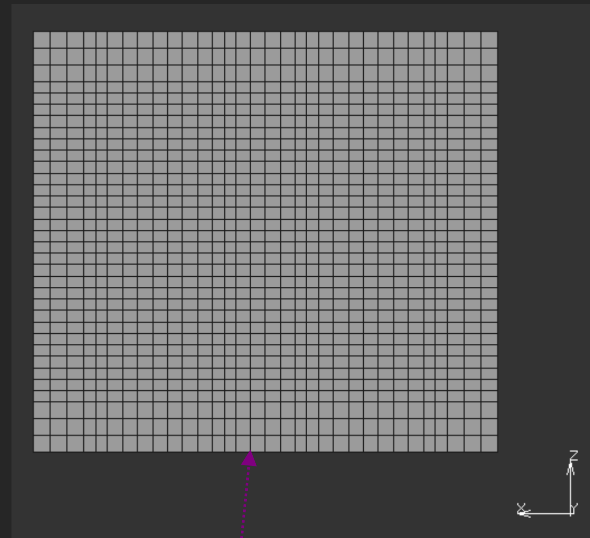


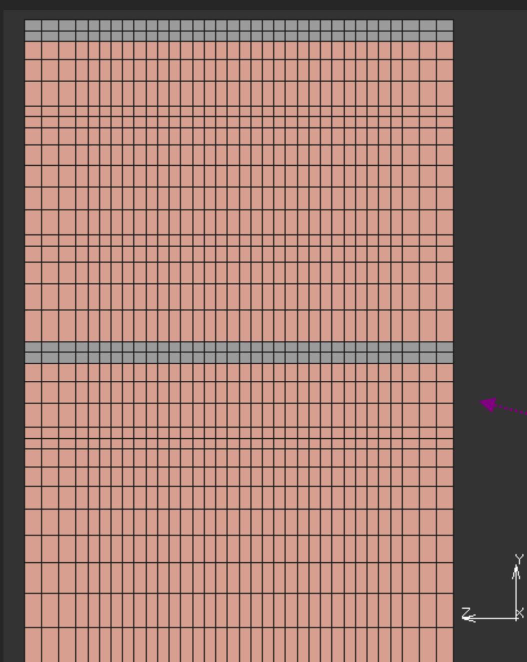
17480 nodes, 11854 solid elements

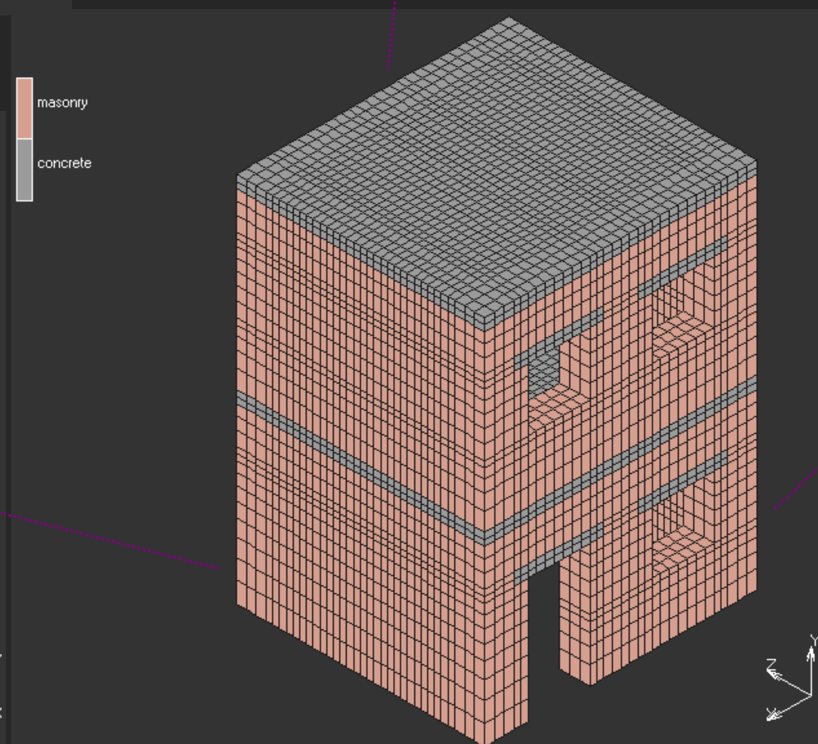
MODEL 3, *reinforced concrete slabs and beams at floors levels*

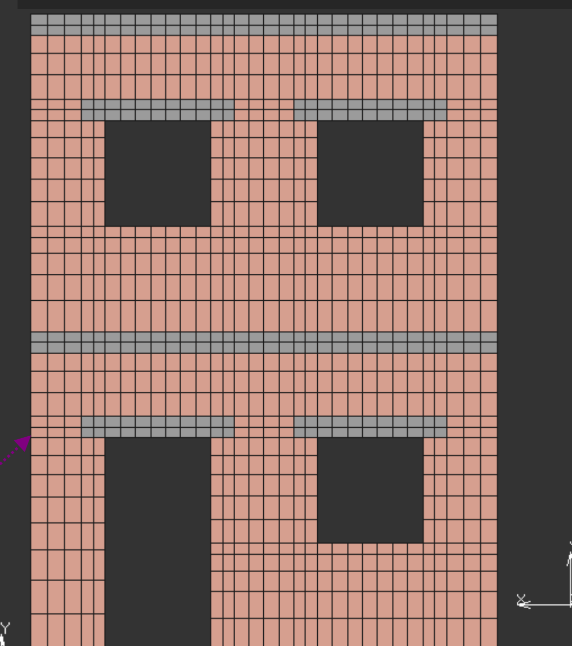
19488 nodes, 13874 solid elements



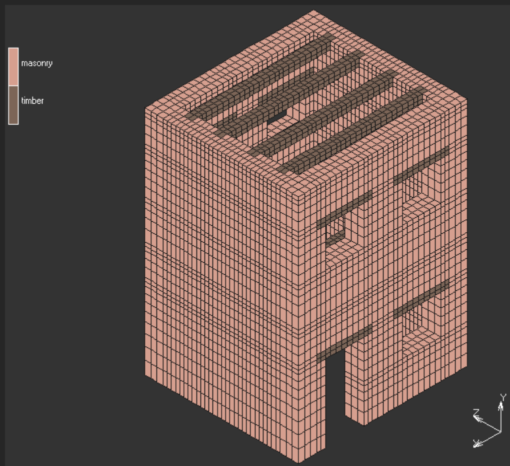


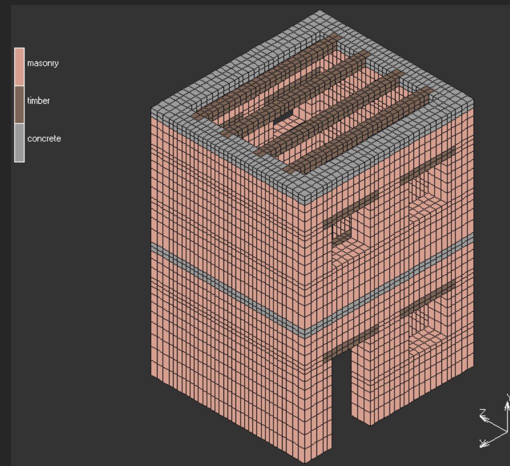


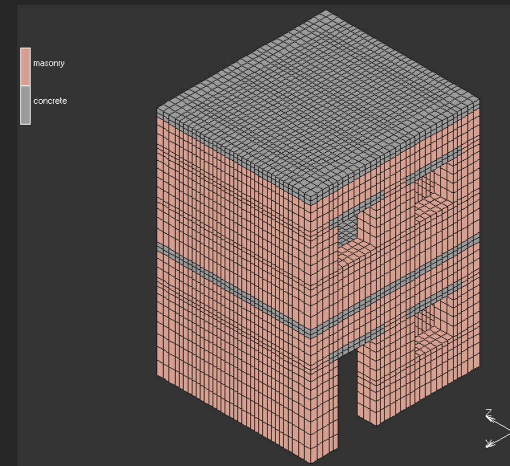


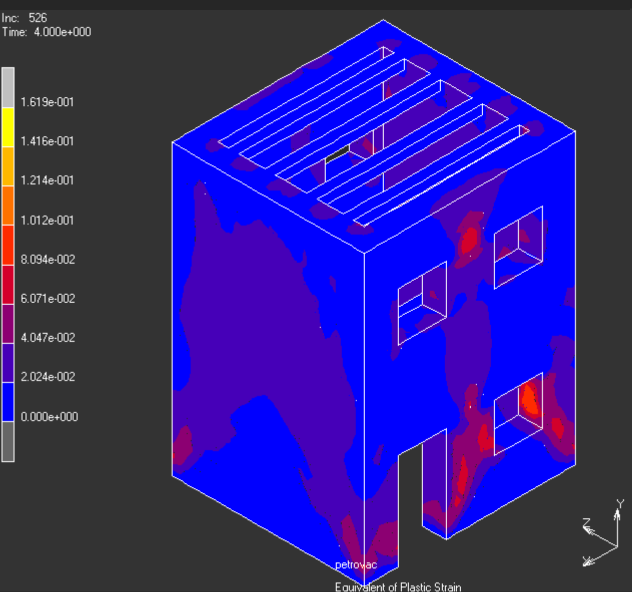


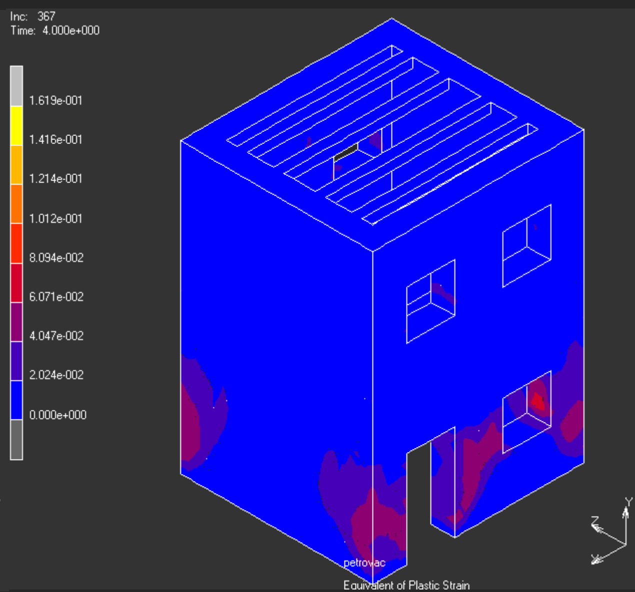
Equivalent plastic strains

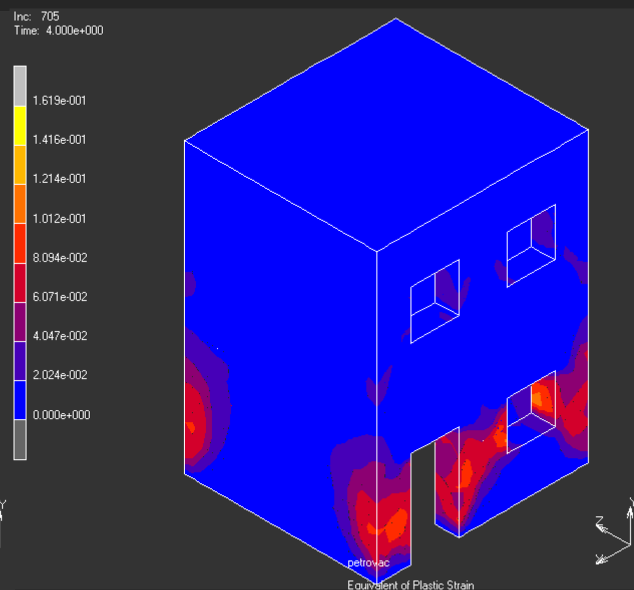












ΜΟΝΤΕΛΟ: 1 2 3

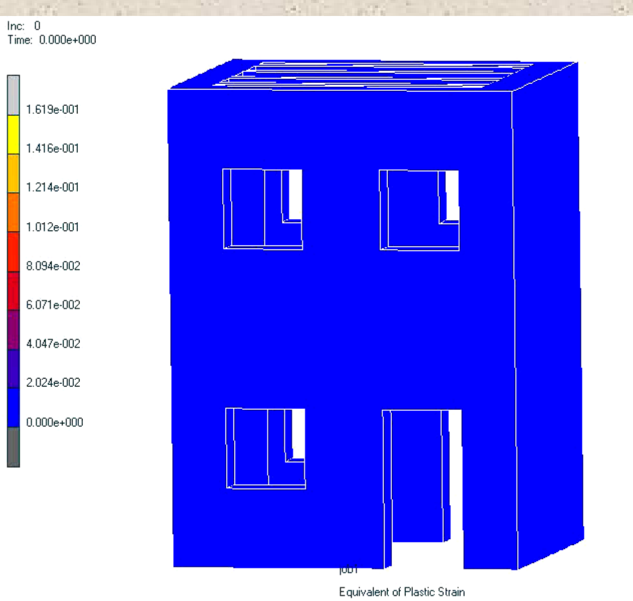
Conclusions

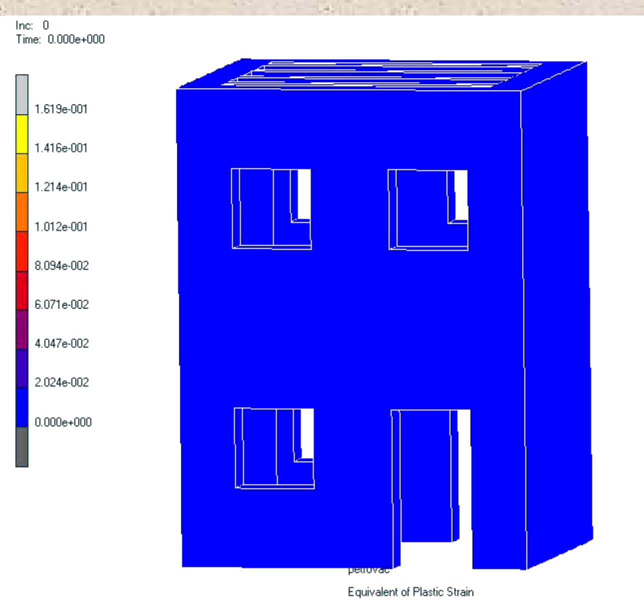
The construction of horizontal reinforced concrete beams at the floor levels (Model 2), or the replacement of the old wooden floors with reinforced concrete slabs (Model 3), lead to a stiffer structure with reduction of deformations, special to the upper floor.

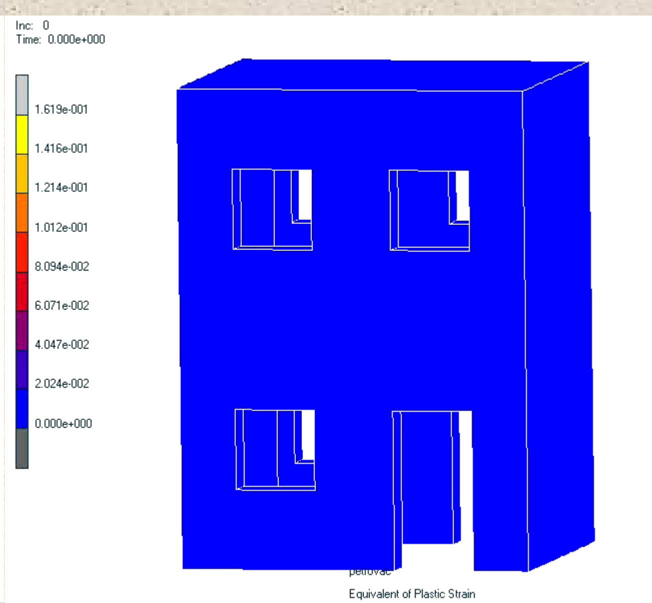
Higher seismic intensity influences basic the first floor, special for Models 2 and 3.

Areas with maximum deformations are localized at the walls which are vertical the seismic direction and special around the openings and at the middle of the pessary.

The construction of horizontal reinforced concrete beams at the floor levels, lead to the better structural system (from the examined models).





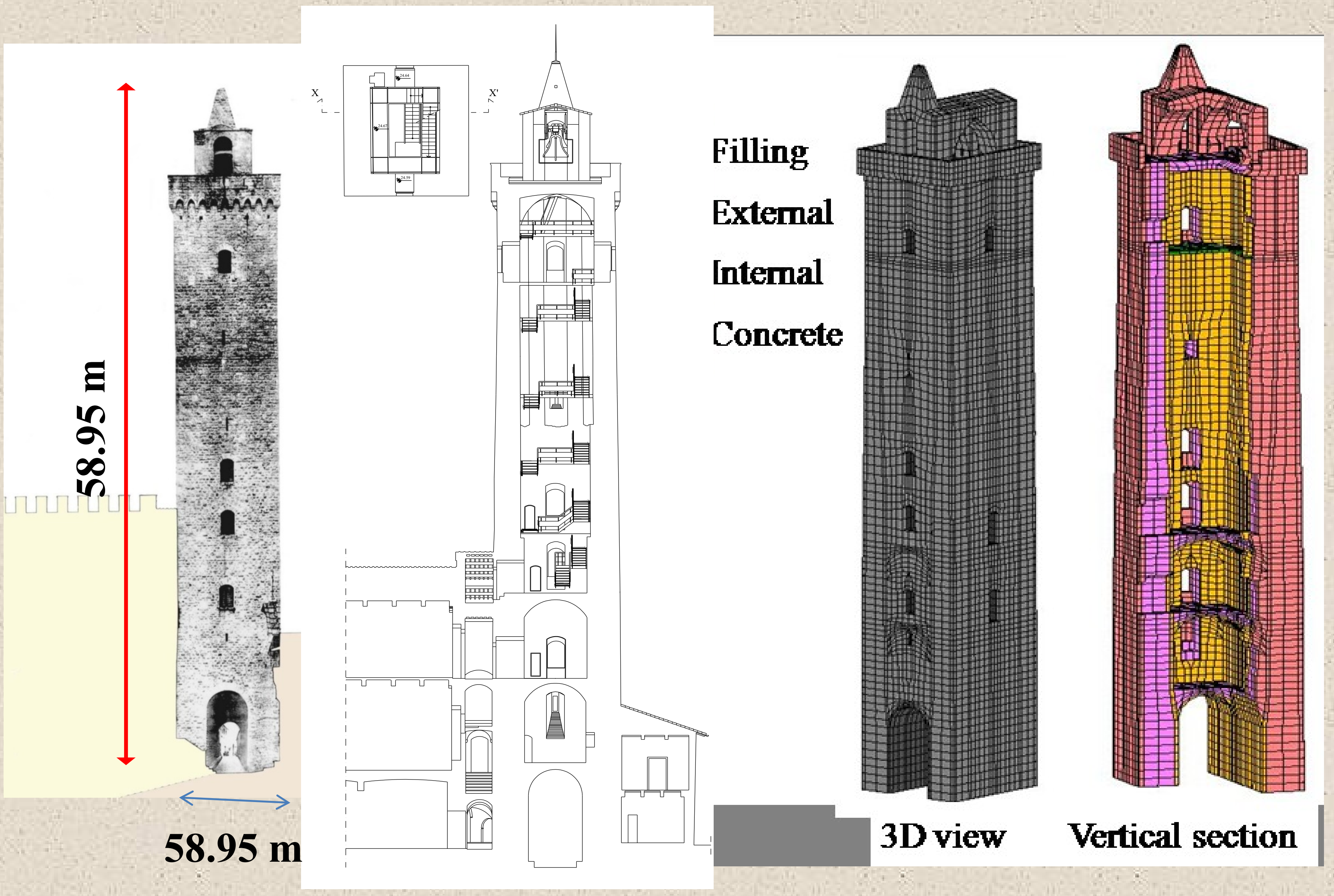


Strengthening of masonry using metal reinforcement. A parametric numerical investigation

Historic masonry tall tower, "*Torre Grossa*"

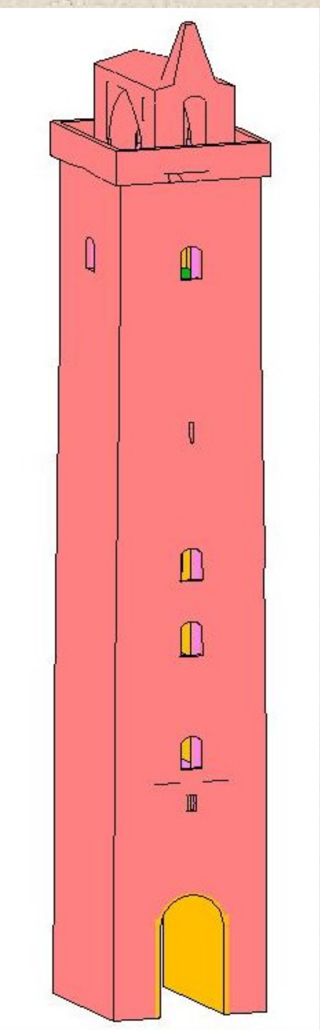
Dated back as thirteenth century and is located in Piazza Duomo (Square of the Cathedral). Town of San Gimignano, Tuscany (Italy).

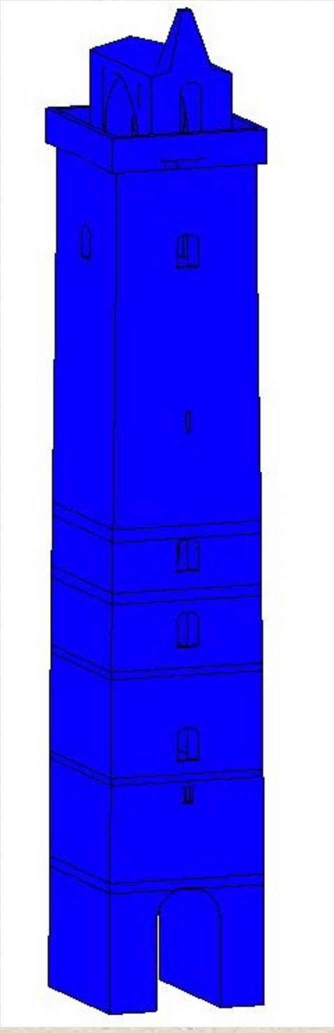
M. E. Stavroulaki, Michele Betti, G.E. Stavroulakis, 'Strengthening of masonry using metal reinforcement. A parametric numerical investigation', *International Conference PROHITECH (Protection of Historical Buildings by Reversible Mixed Technologies),* Rome, 21-24 June 2009.

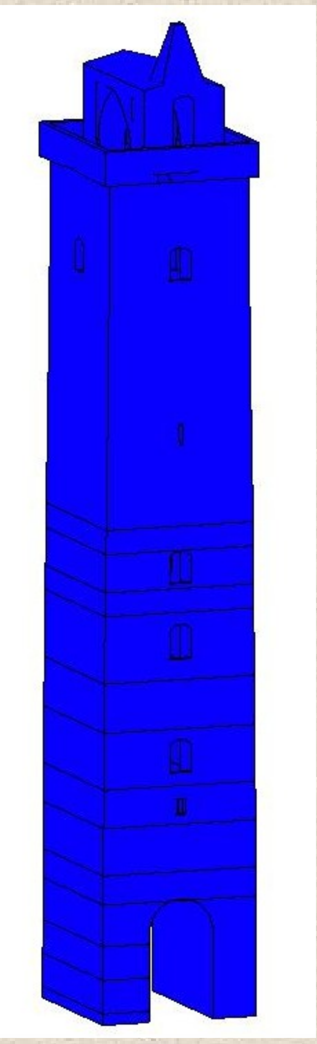


Prohitech09 M.E. Stavroulaki, G. Bartoli, M. Betti, G.E. Stavroulakis

Finite element models





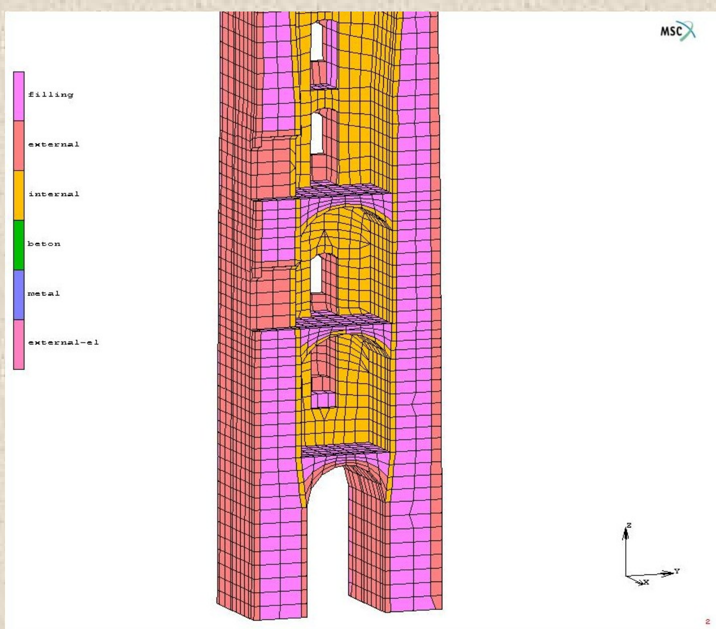


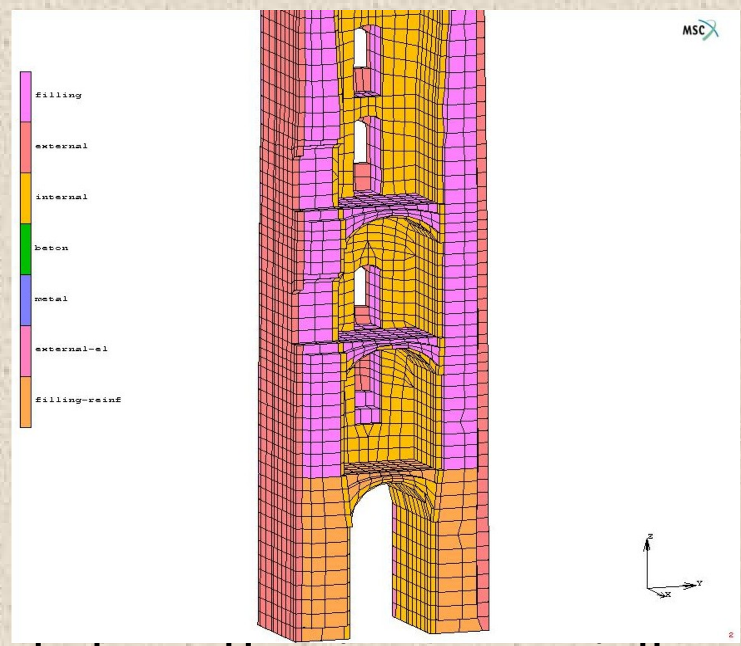
Model A: tower without any reinforcement

Model B: tower with the first group of prestress cables located around the masonry

Model C: tower with the second group of prestress cables located around the masonry

M.E. Stavroulaki, G. Bartoli, M. Betti, G.E. Stavroulakis

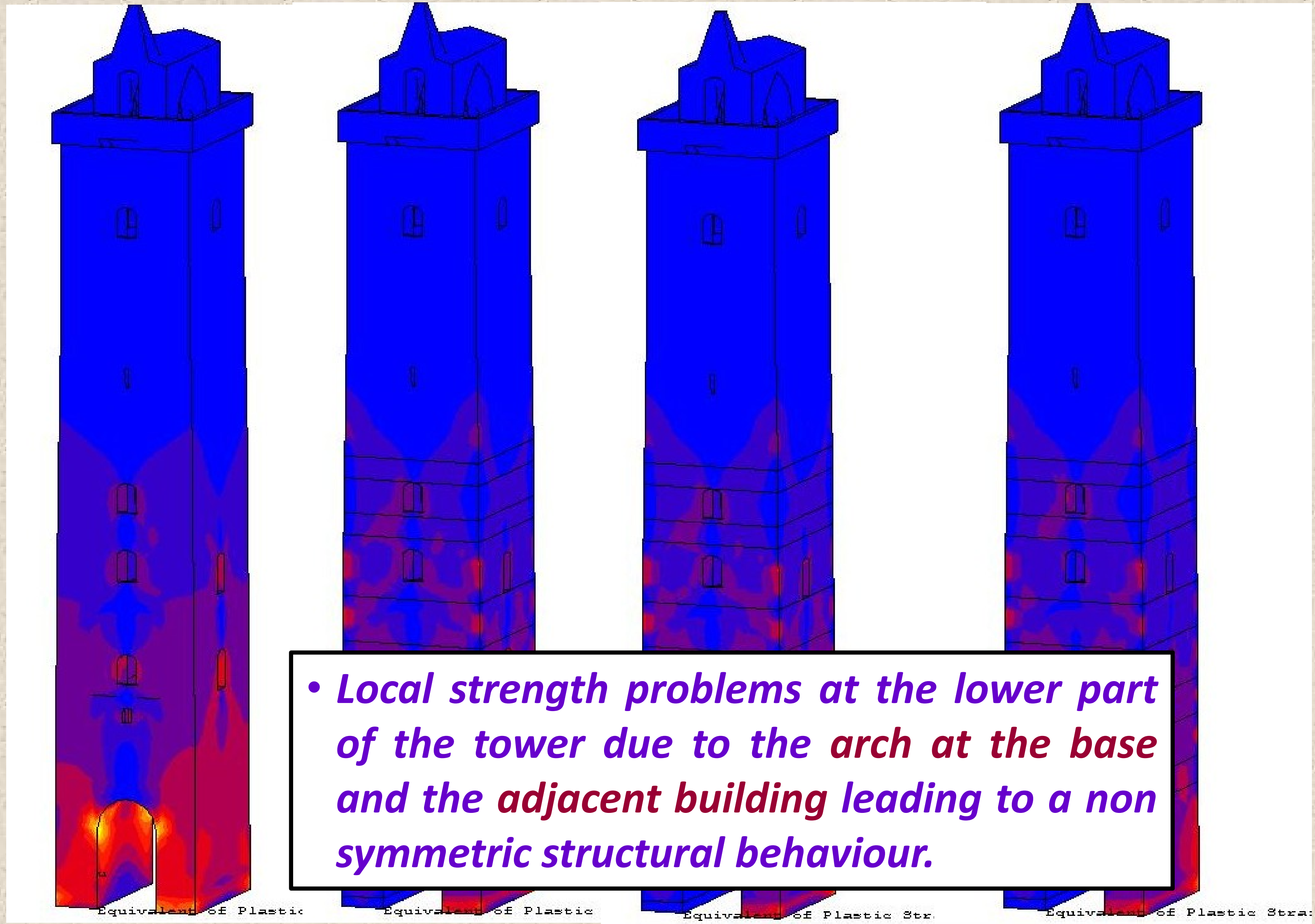




Need of applying additional local strengthening, especially at the lower first part of the model appeared.

- **Model D:** tower with the second group of prestress cables (model C) but considering internal filling material at the lower part with almost double strength (like the internal brick masonry);
- **Model E:** tower with the second group of prestress cables (model C) but considering internal filling material at the lower part with high enough strength.

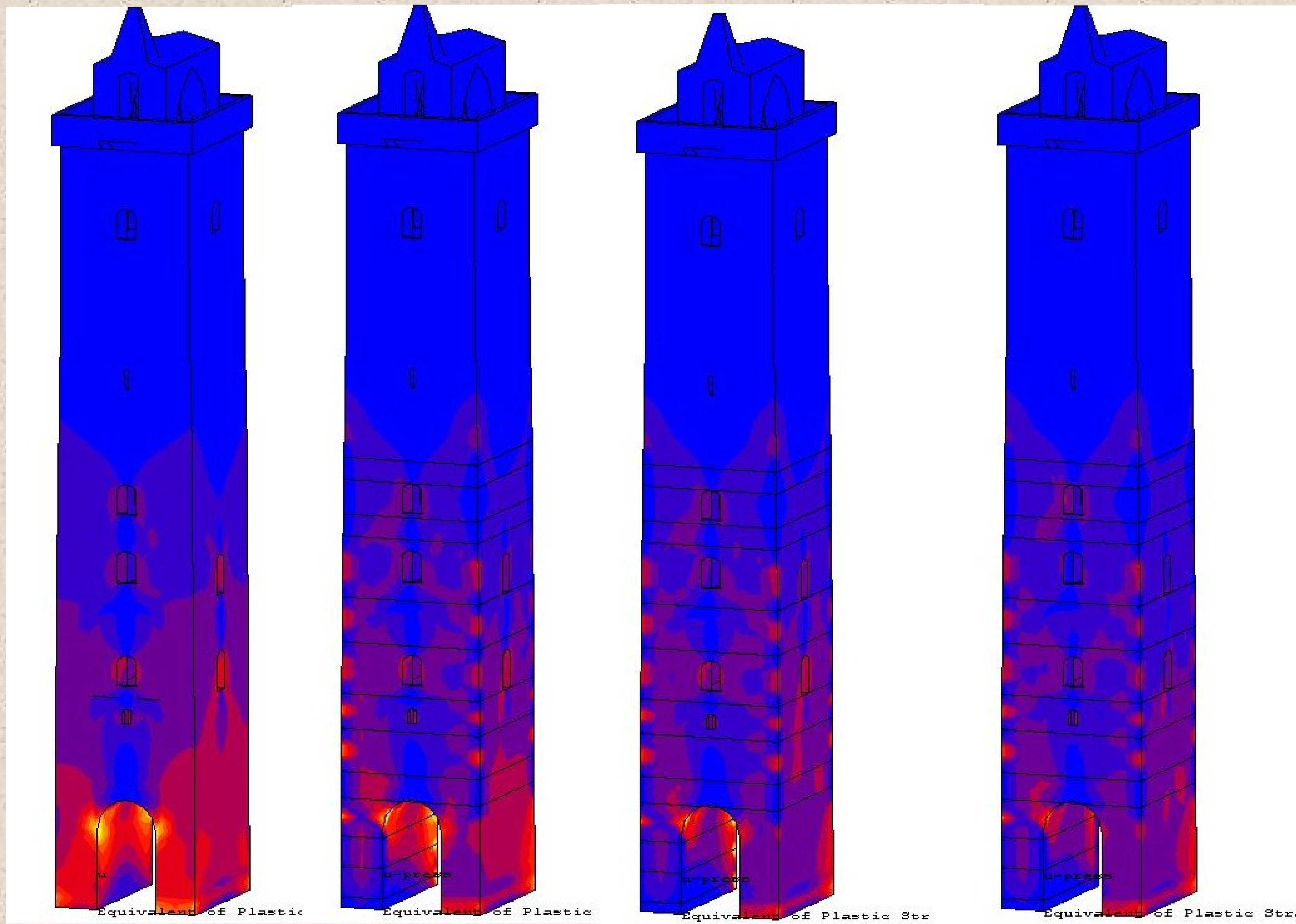
Equivalent plastic strains



- *Local strength problems at the lower part of the tower due to the **arch at the base** and the **adjacent building** leading to a non symmetric structural behaviour.*

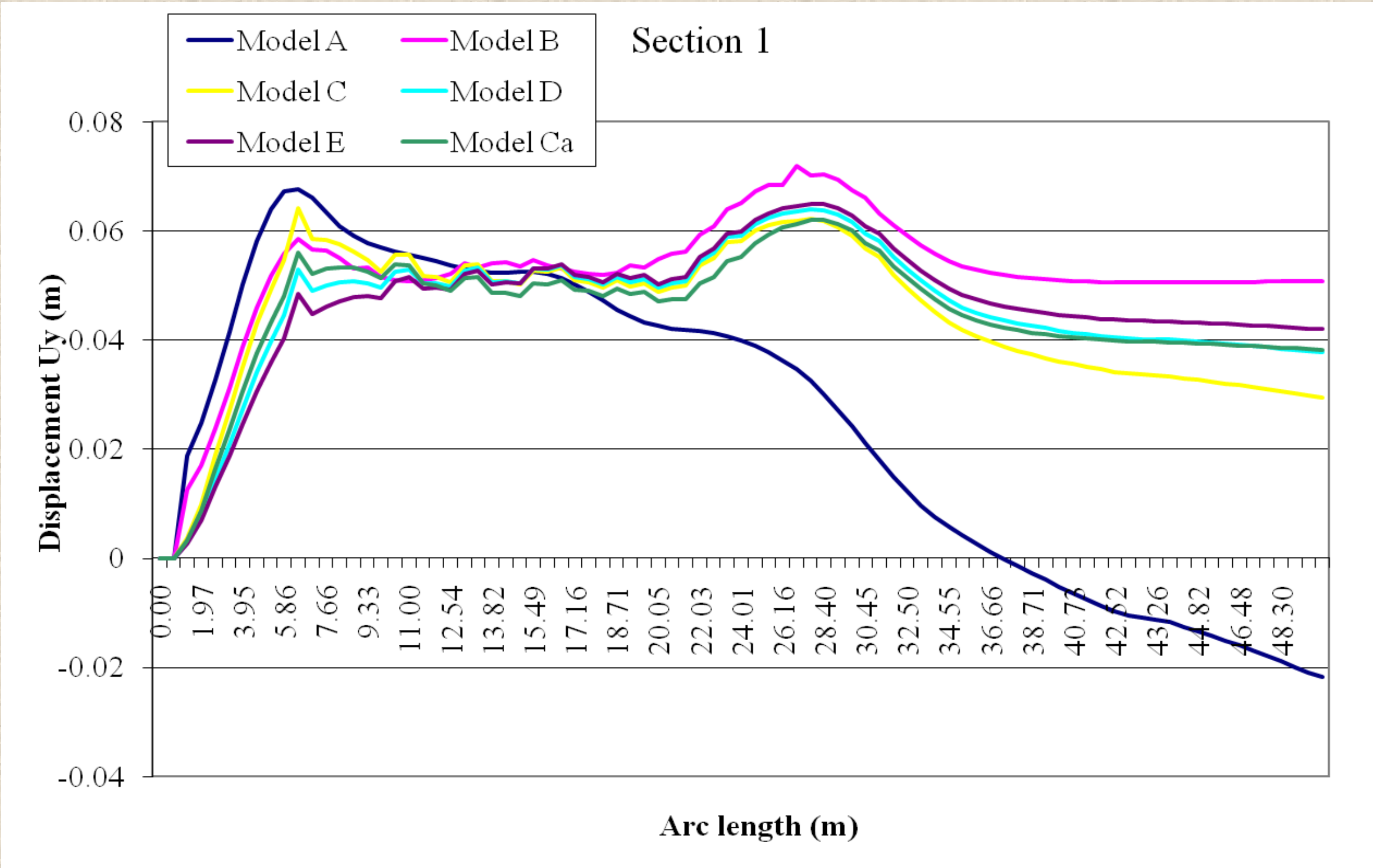
Model A Model C Model D Model Ca

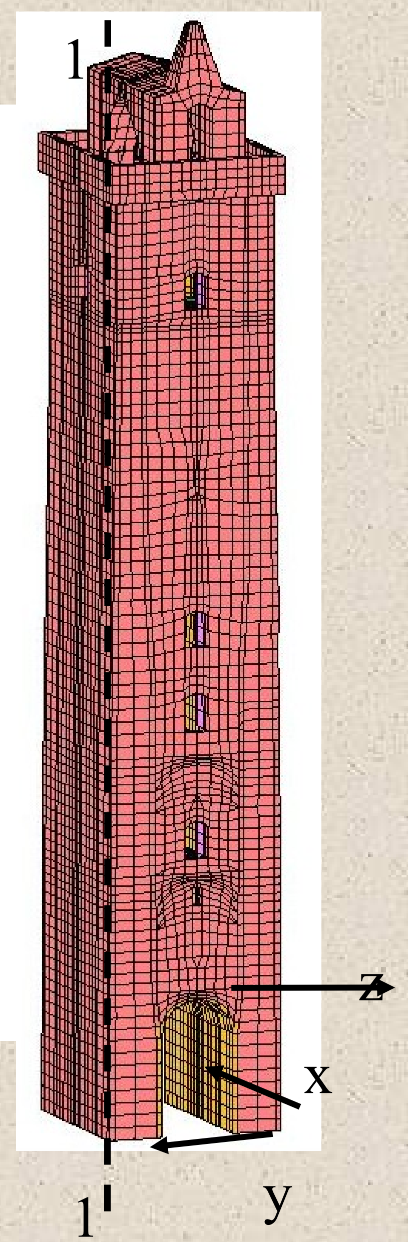
Equivalent plastic strains



Model A **Model C** **Model D** **Model Ca**

Results





Displacement Uy (out of plane) across section 1 (final time step)

- *Prestress cables and also strengthening of material* ***influence the overall mechanical behaviour***.

Analysis of Masonry Structures – *Rehabilitation*

-When only the **perimeter walls from the old building** are kept, **another structural system** is placed inside or/and outside the initial structure.

Proper connections are done at special places in order to have **cooperation between these two different structural systems** (*different material, like reinforced concrete or steel, different stiffness*).

Rigid connection leads to a **composite structure** (*different dynamic characteristics*).

Looseness of this connection, perhaps under a strong earthquake, leads to **pounding phenomena**.

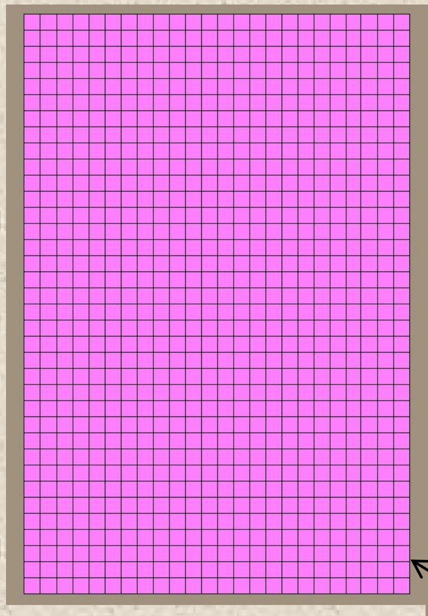
Pounding phenomenon

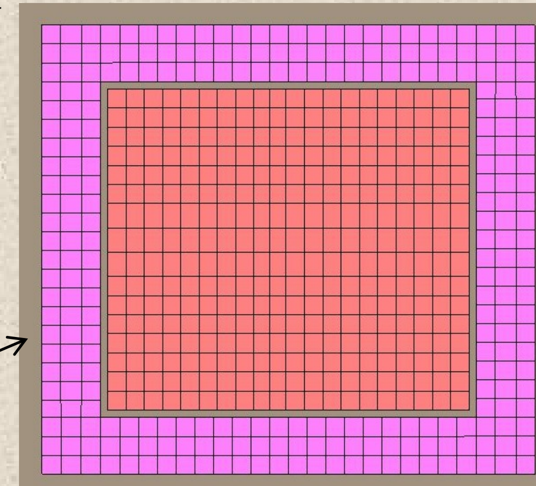
- The Interactions between insufficiently separated structures, or their parts, due to the out-of-phase vibrations during major earthquakes, **(earthquake-induced structural pounding),** may lead to considerable damage or can be even the reason of the structure's total collapse.
- The phenomenon of friction which is developed between the adjacent structures, under a dynamic excitation influence the dynamic response of the structures

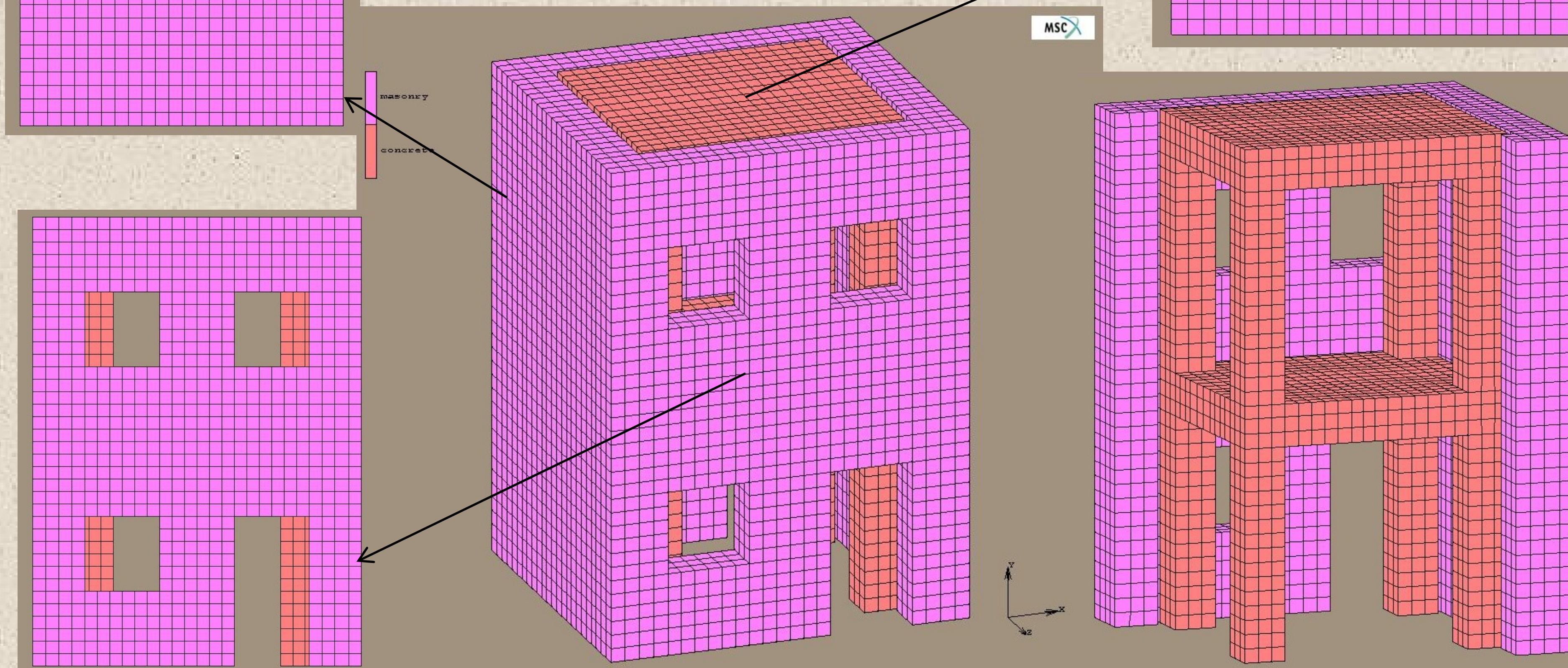
→ ***Must be included in the analysis.***

Dynamic response of masonry walls in connection with reinforced concrete frame

Adjacent structures – Bounding phenomena





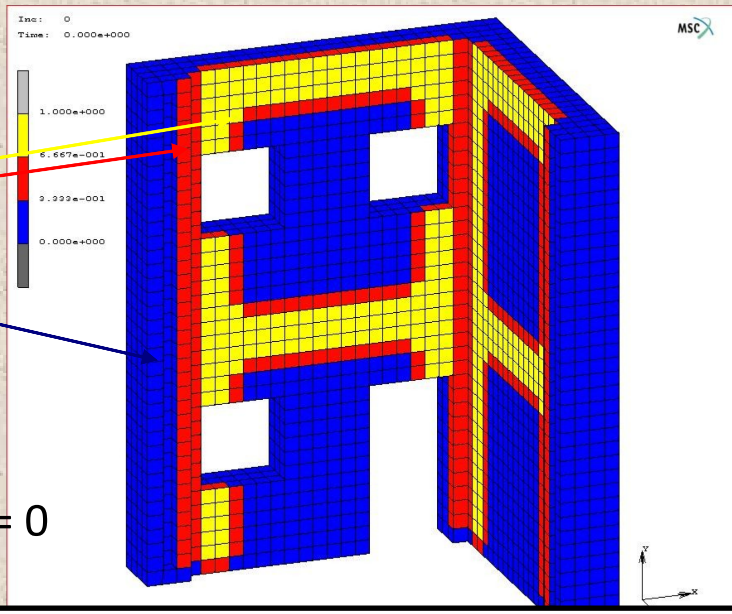


M.E. Stavroulaki, K. Pateraki (2013), 'Dynamic response of masonry walls in connection with reinforced concrete frame', '*Recent Advances in Contact Mechanics', Lecture Notes in Applied and Computational Mechanics* 56, Ed. G.E. Stavroulakis, Springer, pp. 257-273.

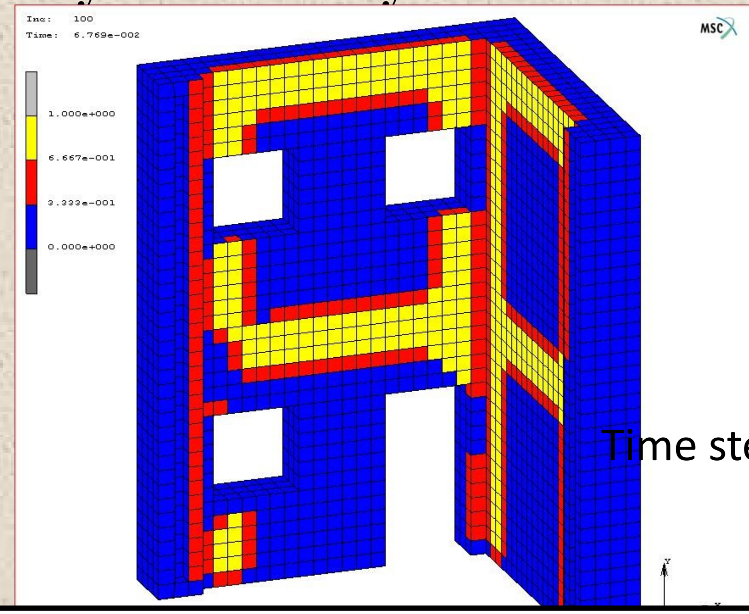
Results of transient dynamic analysis

In contact

Without contact

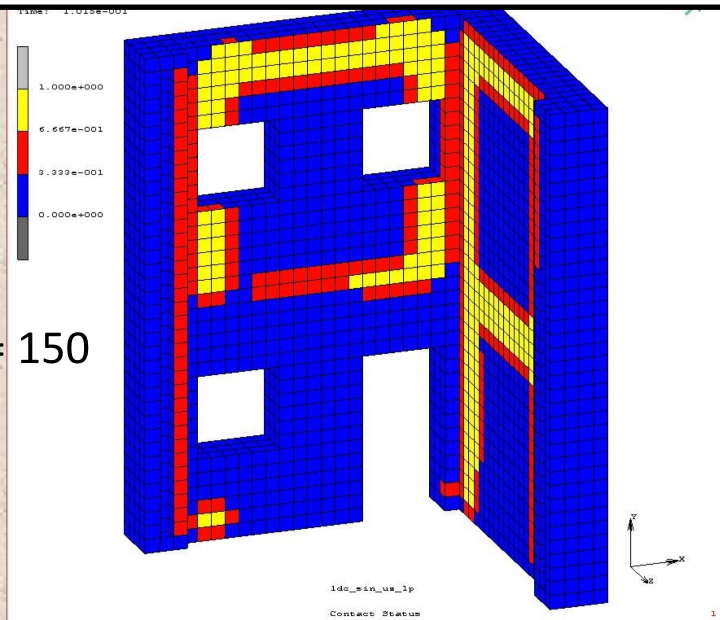


Time step= 0

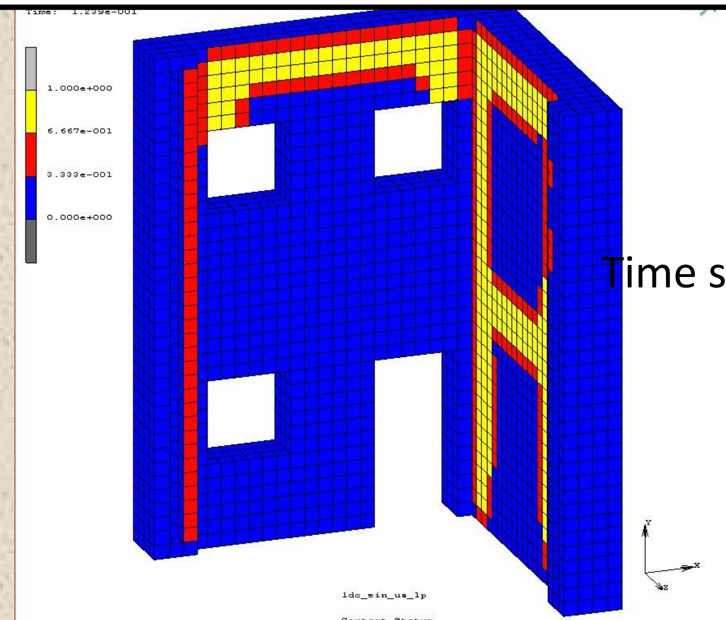


Time step= 100

Base excitation: Displacemen in Z direction (Uz)
(Indication of contact or non –contact codition - Contact status)



Time step= 150



Time step= 183

Reuse of stone masonry buildings and the seismic behavior of the composite structures

- ✓ Undertaking an integrated proposal for dealing with an existing building
- ✓ Compare methods & optimize results.
- ✓ Interaction study of different structural systems.
- ✓ Evaluation of the architectural proposal for reuse by simulating .

Efstathia Tavlopoulou, Ifigenia Tziveleka and Maria Stavroulaki, ‘REUSE OF STONE MASONRY BUILDINGS AND THE SEISMIC BEHAVIOR OF THE COMPOSITE STRUCTURES ‘,8th GRACM International Congress on Computational Mechanics Volos, 12 July – 15 July 2015

Finite element model

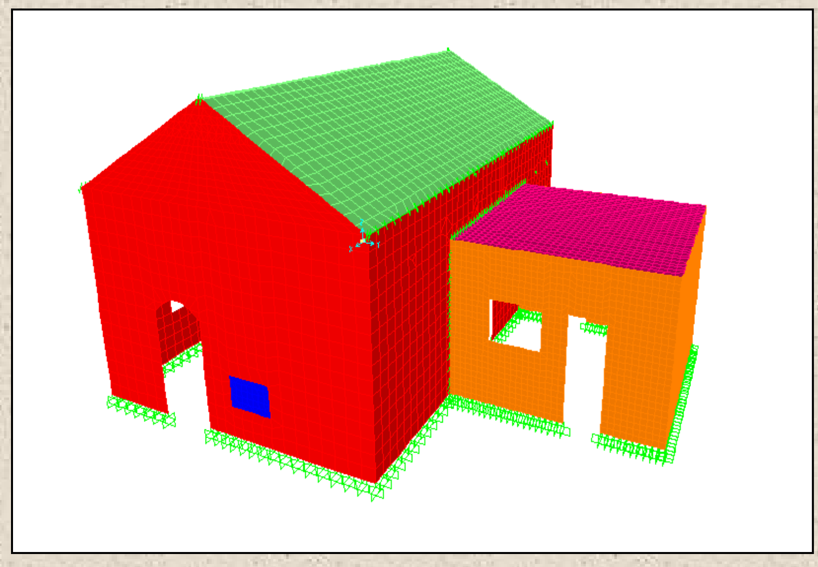
For the simulation via FEM, it is important to use a reliable model taking into account:

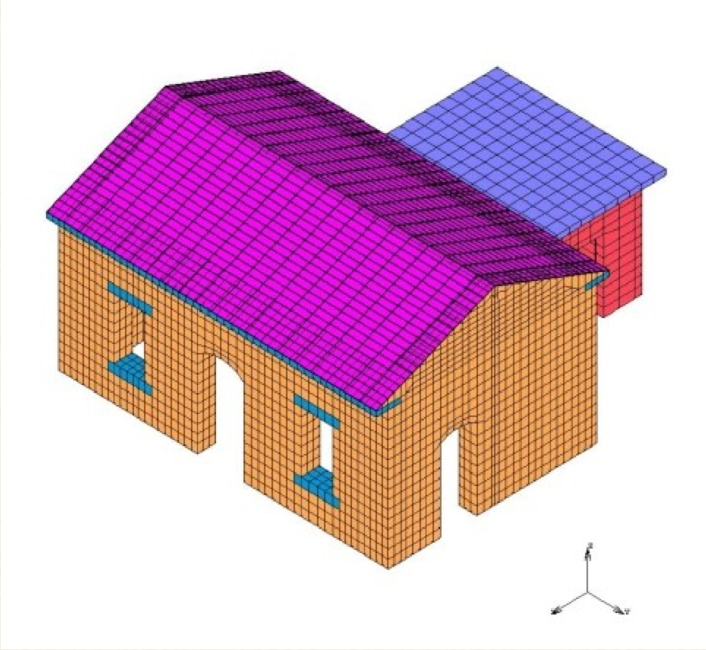
complexity of geometry, structural system, quality & current condition of materials, additions and repairs during structure's lifetime.

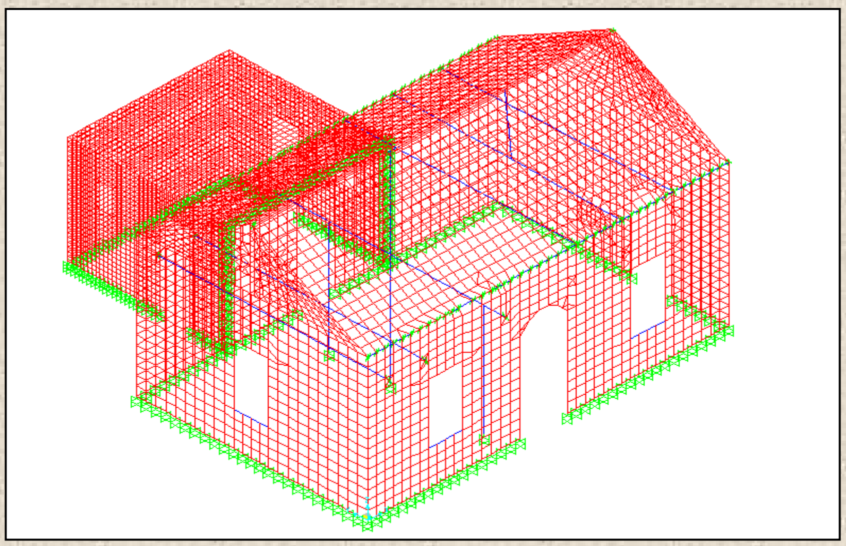
Masonry structures have dynamic characteristics quite different from those of reinforced-concrete or steel designs. (Densely placed modes are presented, as in most stiff massive structure and more than one mode participates significant.)

Dynamic measurements – Calibration & verification of the models

- Useful for the **identification of mechanical properties and soil restraints.**
- The comparison of the fundamental frequencies and modes of vibration obtained from the finite element model with the frequencies and modes obtained with measurements on-site, provide a way to **evaluate the reliability of the simulation and calibrate the FEM model.**

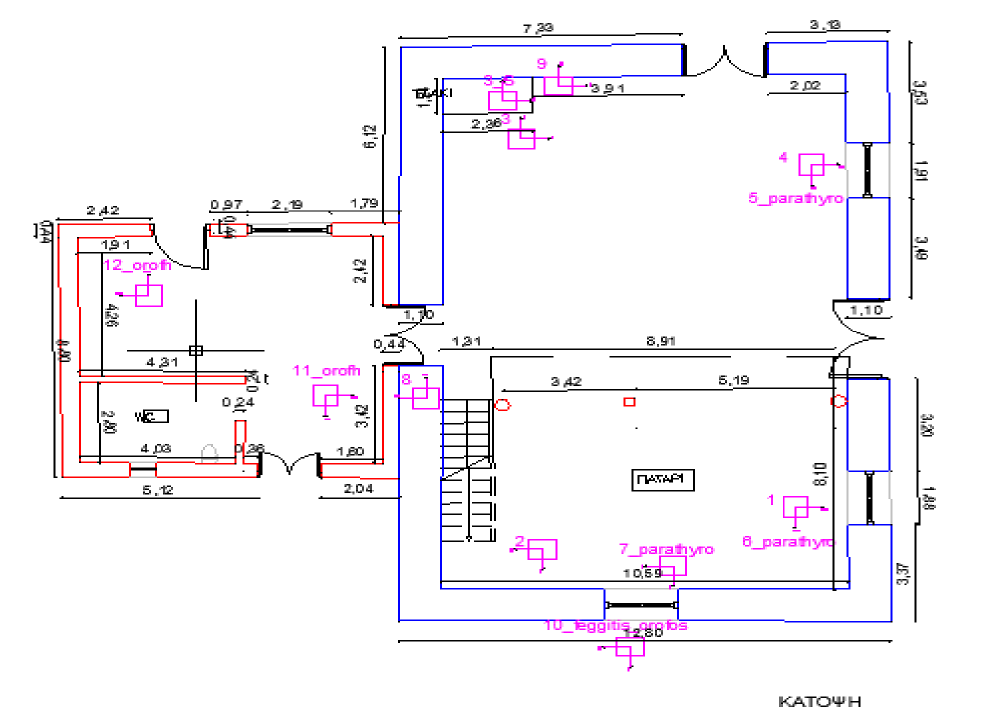






Dynamic measurements
- Ambient Vibration Tests -

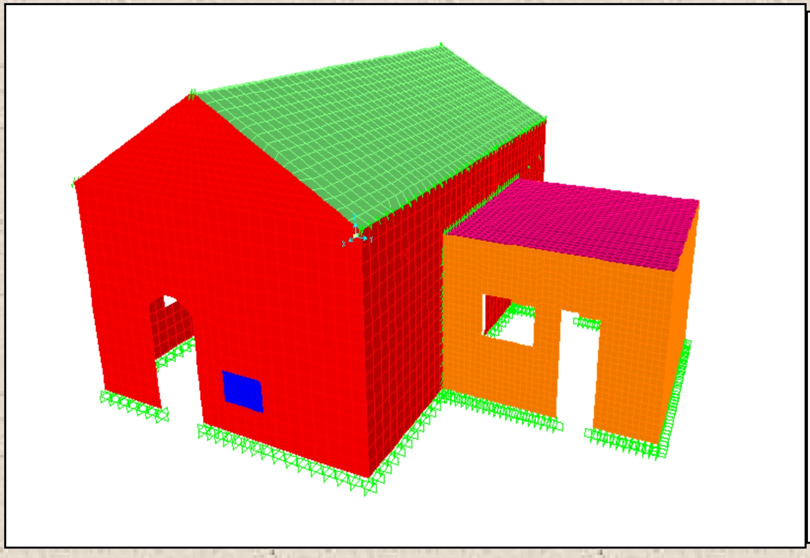
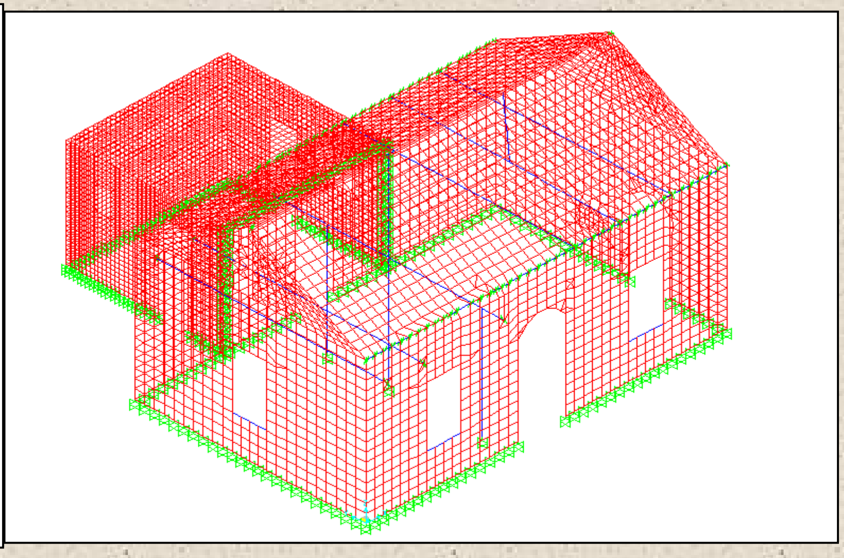
Recorded acceleration in the time domain through accelerometers and in situ ambient vibration experiments → extraction of natural frequencies → displacements of the structure



Terrace plan showing the accelerometers ' position (purple colour).

Modeling and analysis with SAP

Existing building

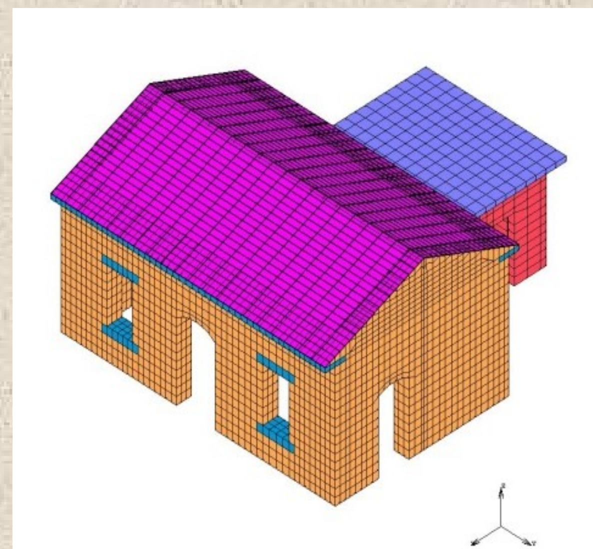



a) Finite elements used (different materials) b) Discretization of structure.

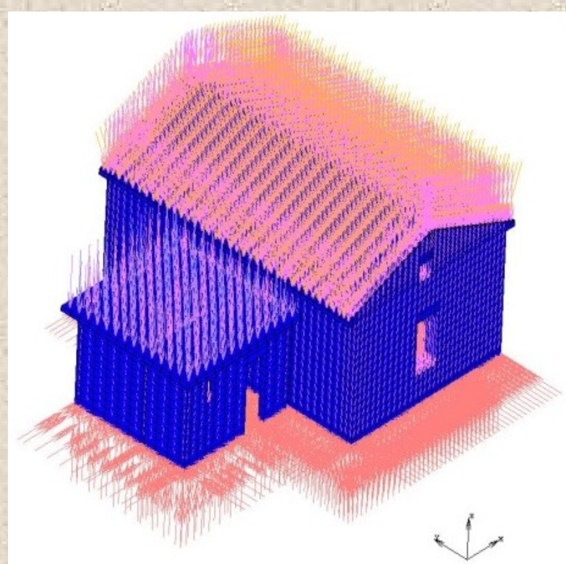
- Masonry, concrete slab: 4-node shell-thick elements with 6 DOF three dimensional modelling of the structure, fixed at its base
- Wooden & concrete linear elements: frame elements
- Roof: shell-thin elements

Modeling and analysis with Marc

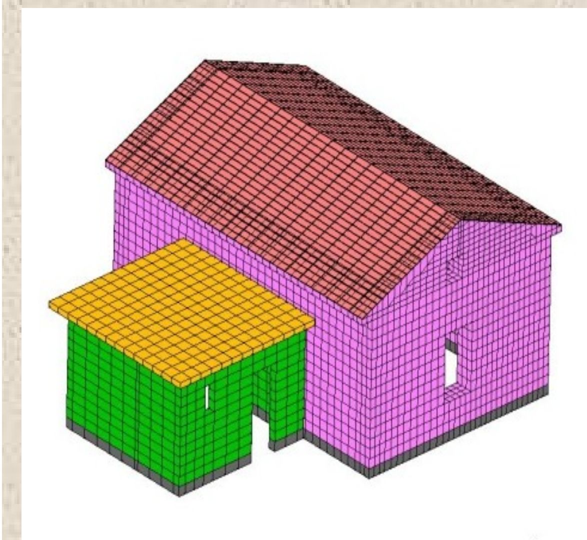
Existing building



a) finite elements used in Marc



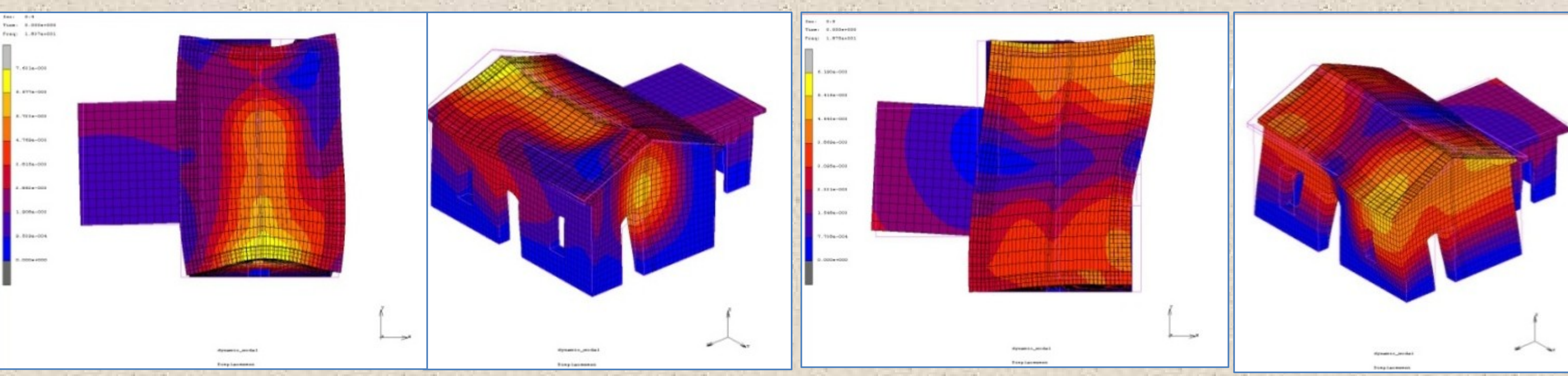
b) boundary conditions



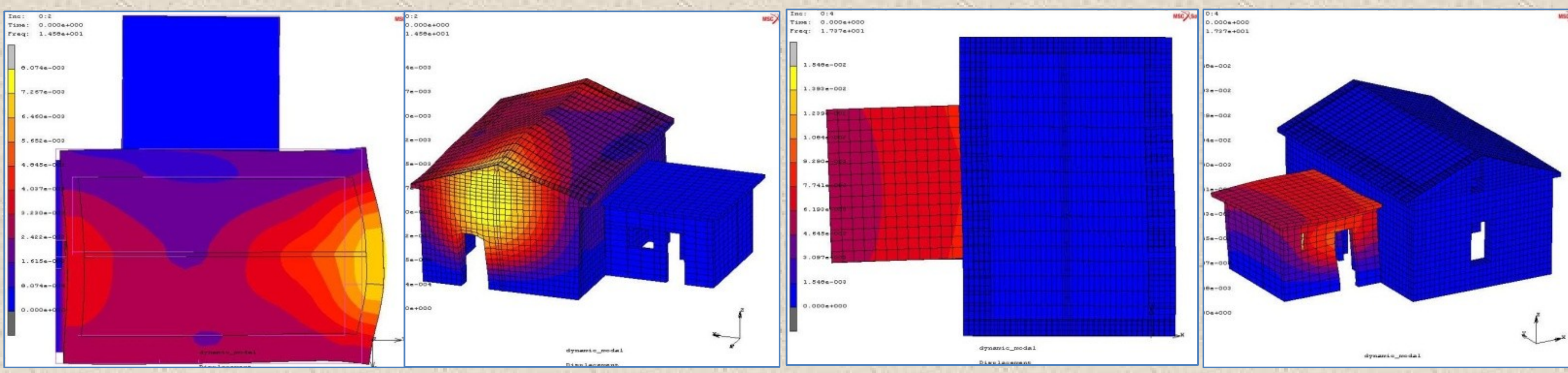
c) contact bodies

- Three dimensional modelling of the structure.
- Hexahedral Elements with eight nodes (3 DOF) were used for the discretization of the Structure.

Dynamic characteristics



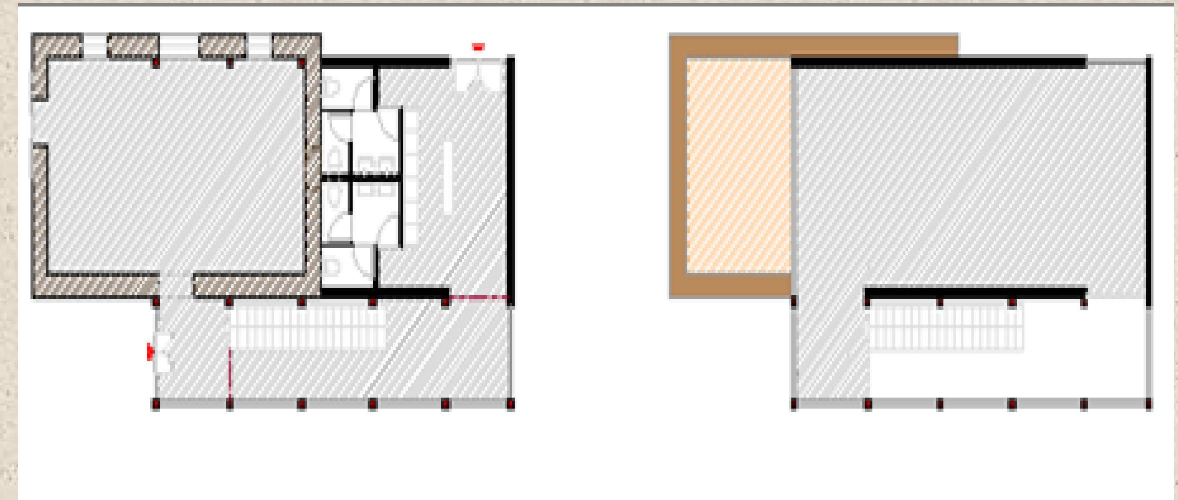
deformed structure in MARC_I model for modal f4=18.37 Hz and f5=18.75 Hz

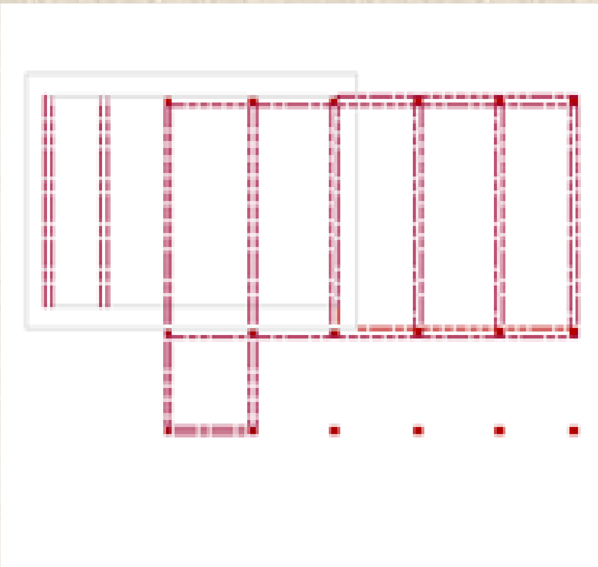


deformed structure in MARC_II model for modal f2=14.58 Hz, and f4=17.37 Hz.

Architectural proposal of reuse

MAIN IDEA: " ***Multicultural Hall - Link and smooth transition from the old to the new.***



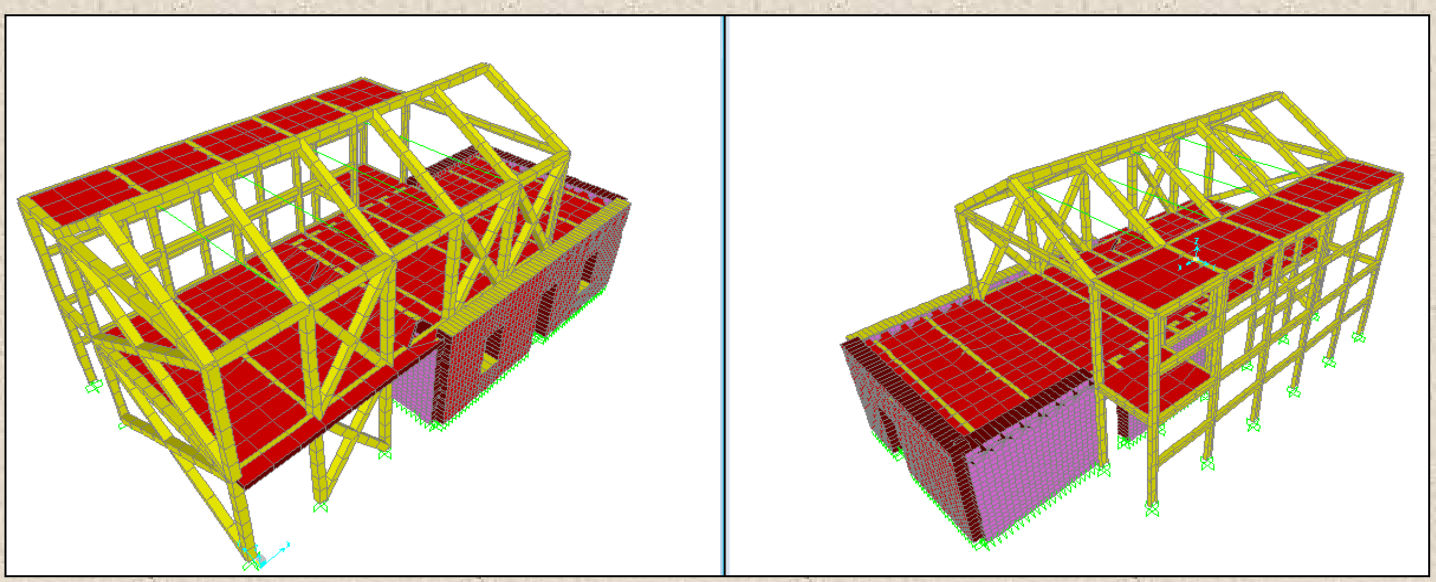


a) ground floor *b) first floor* *c) Structural system*

Modeling and analysis with SAP

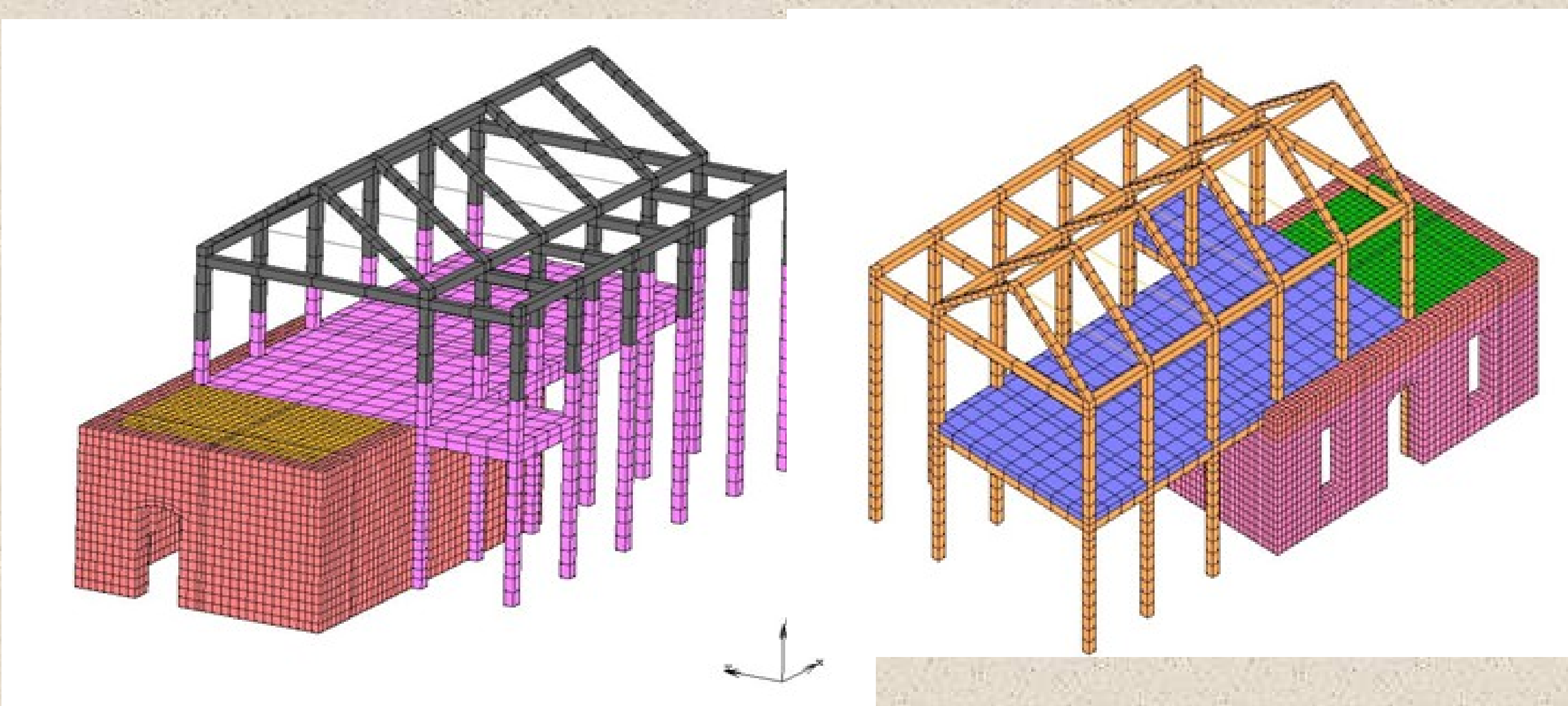
Architectural proposal of reuse

Initial stone masonry is maintained
New metal frame modelled with frame elements
Cement walls calculated as loads on the metal frame
Glass elements not taken into account
Compounds considered to be fixed.



Modeling and analysis with Marc

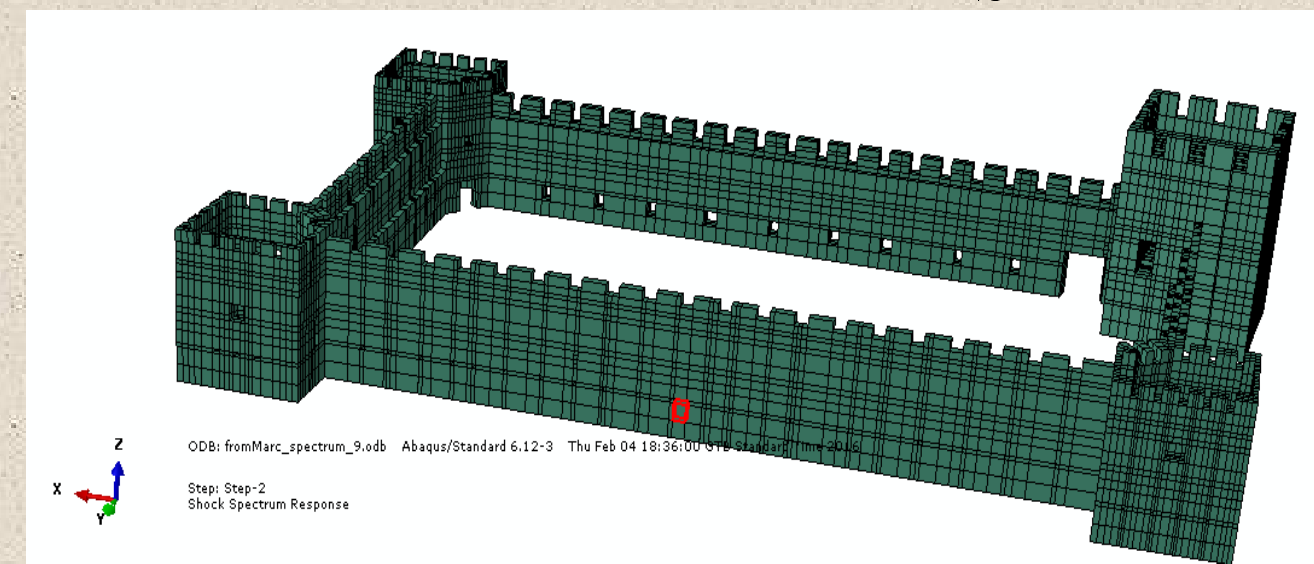
Architectural proposal of reuse



a) 3D model finite element in Marc b) contact bodies

Dynamic characteristics of existing building & architectural proposal of reuse, problems.

FRAGOKASTELLO SFAKIA: RESTORATION AND CONSERVATION THROUGH COMPATIBLE ARCHITECTURAL, STRUCTURAL AND CONSTRUCTION MATERIALS

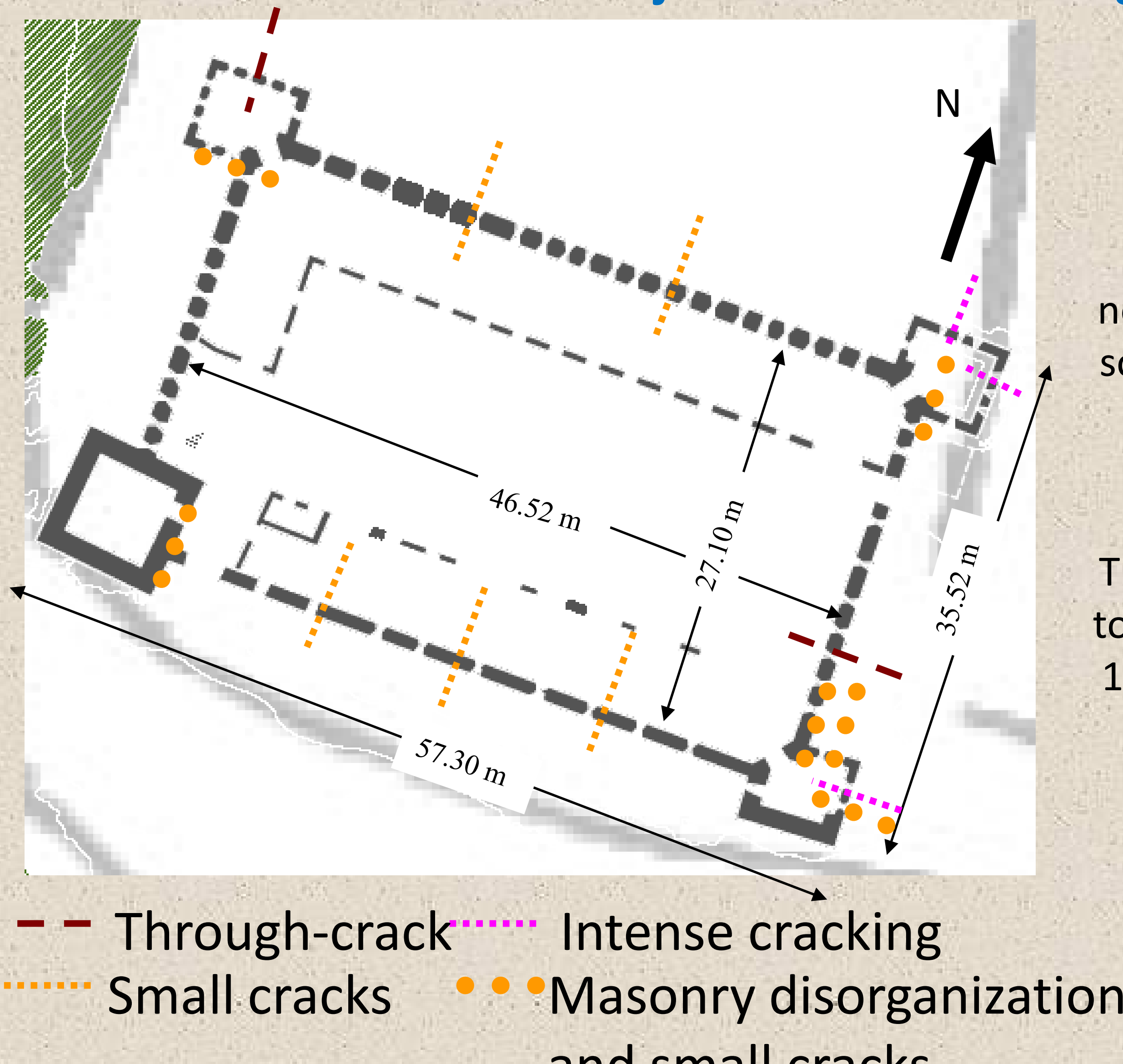


- Maria E. Stavroulaki, Georgios A. Drosopoulos, Efstathia Tavlopoulou, Nikos Skoutelis, Georgios A. Stavroulakis (2017), paper ‘Investigation of the structural behavior of a masonry castle by considering the actual damage’, *Int. J. of Masonry Research and Innovation* (IJMRI) (in press).
- Stavroulaki Maria, Skoutelis Nikos, Maravelaki Noni-Pagona, Drosopoulos Georgios and Stavroulakis Georgios (2017), ‘FRAGOKASTELLO SFAKIA: RESTORATION AND CONSERVATION THROUGH COMPATIBLE ARCHITECTURAL, STRUCTURAL AND CONSTRUCTION MATERIALS’, International conference Coordinating engineering for sustainability and resilience (CESARE’17), Dead Sea, Amman, Jordan 3-8 May, paper 17, pg.158.
- Cheimonas Th., Manoutsoglou E., Stavroulaki M. and Skoutelis N. (2016) ‘CLASSIFICATION OF BUILDING STONES OF THE FRANGOKASTELLO CASTLE, SFAKIA, CRETE’ Bulletin of the Geological Society of Greece,, Proceedings of the 14th International Congress, Thessaloniki, May 2016, vol. L, p. 209-217

- Architectural study and structural condition
- Characterization of the original construction materials and design of compatible restoration mortars and plasters
- Structural finite element analysis
- Restoration proposal

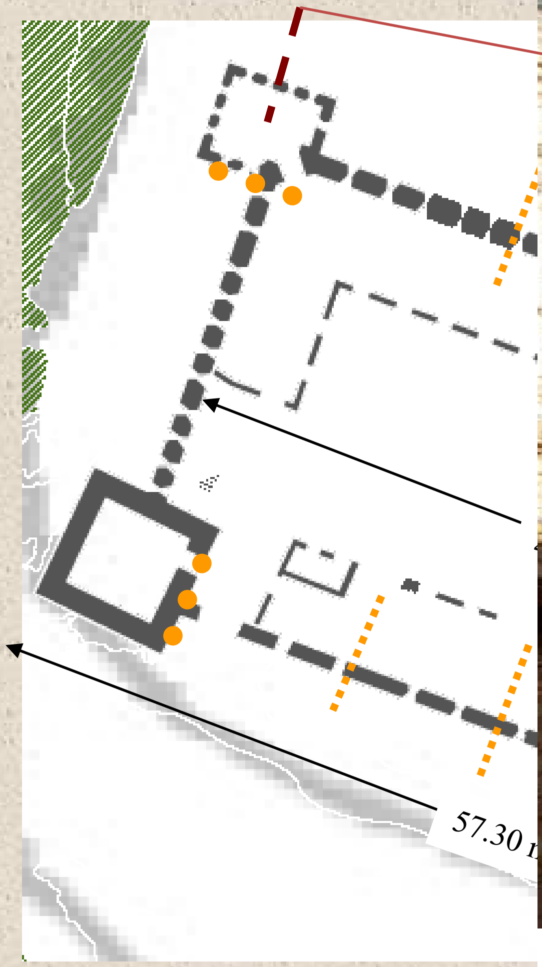
Architectural study and structural condition

Plan view of the carrier and major structural damages



The three towers, northwest, north-east and south-east has an average height of 9 meters. The southwest tower is higher, 15 meters and has a larger base.

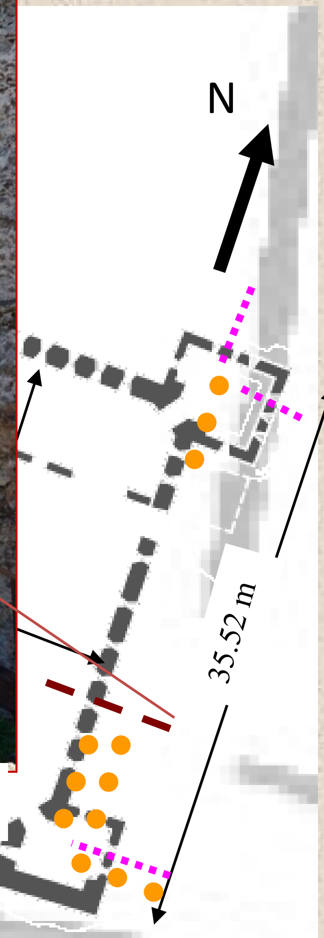
Structural condition



North facade, of the NW tower (internal view)

– – Through-crack

tion

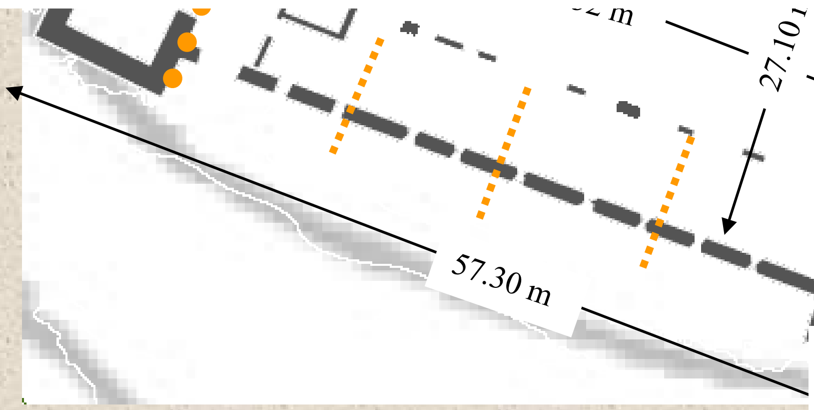


Outside view - Inside view

East wall.

Through-crack

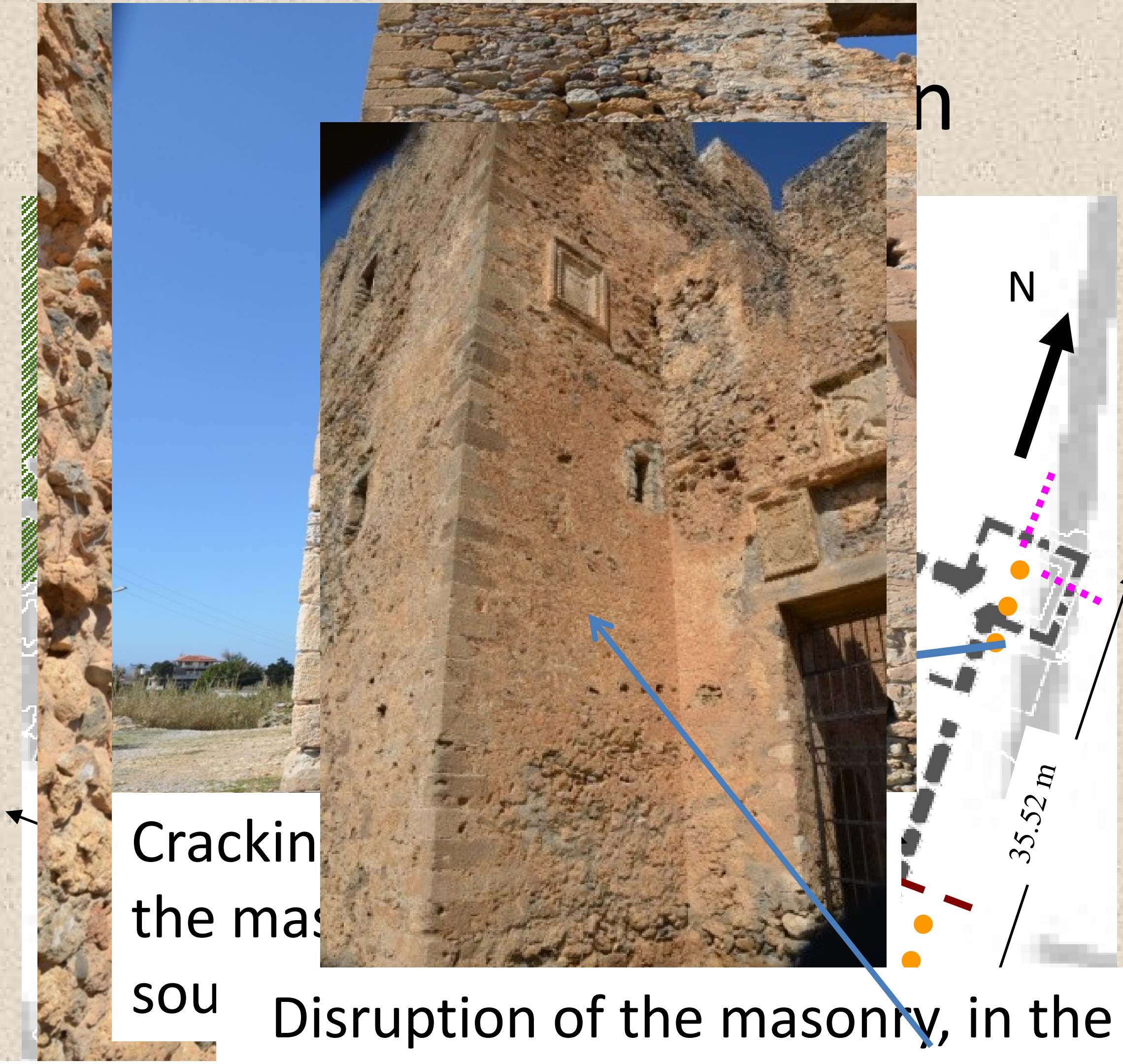
Disruption of the masonry, on the lower level of a south wall



Disruption on the top of a south wall, internal view

Small cracks

Masonry disorganization and small cracks



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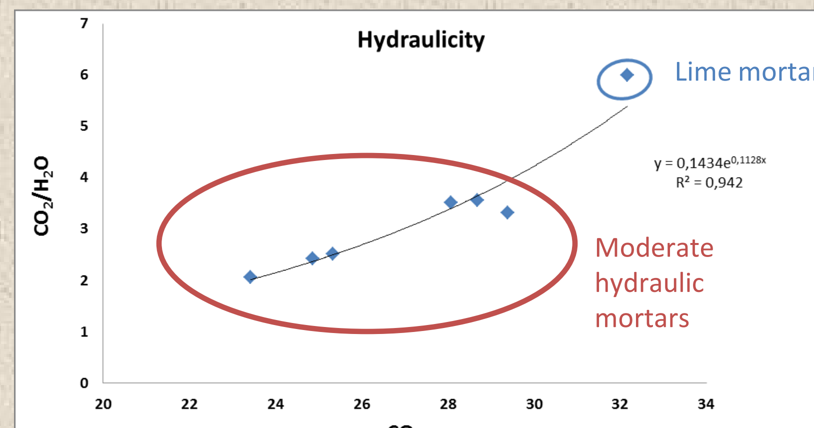
Disruption of the masonry, in the connection area between the south wall and the south west tower.

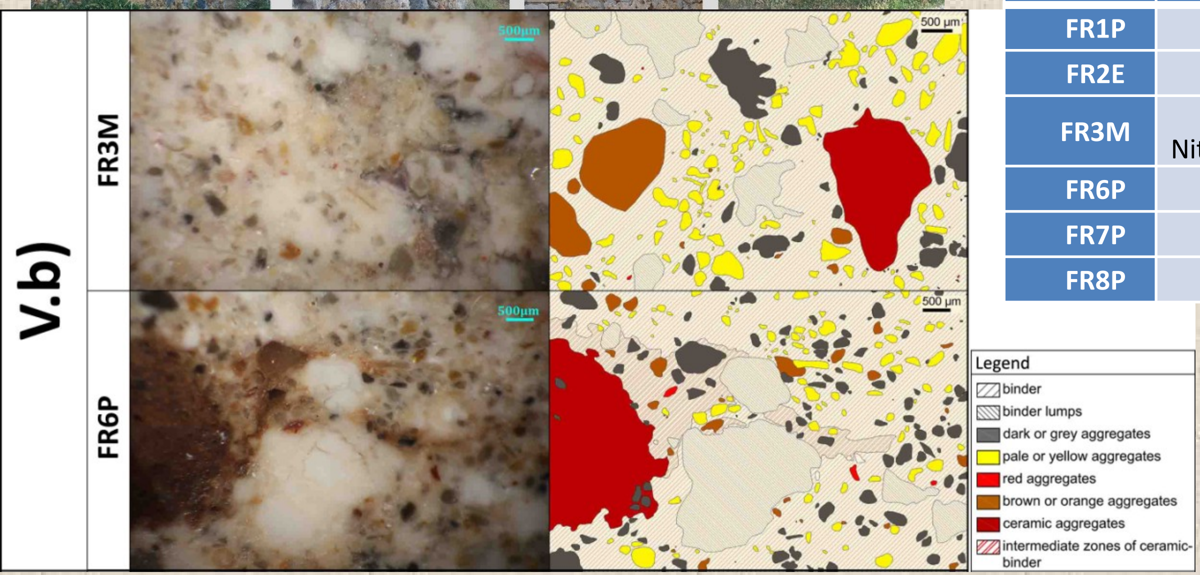
Masonry disorganization and small cracks

Characterization of the original construction materials and design of compatible restoration mortars and plasters



The analysed mortars exhibited a moderate hydraulicity

Sample	Mineralogical composition
FR1P	Calcite, Quartz, Dolomite, Aragonite, Illite, Augite
FR2E	Calcite, Quartz, Dolomite, Aragonite, Illite
FR3M	Calcite, Quartz, Dolomite, Aragonite, Illite, Potassium Nitrate, Halite
FR6P	Calcite, Quartz, Dolomite, Aragonite, Illite
FR7P	Calcite, Quartz, Dolomite, Kaolinite, Illite, Albite, Augite
FR8P	Calcite, Quartz, Dolomite, Kaolinite, Illite, Augite



Optical microscopy of cross sections and the re-designed mortar profiles to measure the mortar aggregate grain size. A very compact microstructure was observed explaining the mortar longevity.

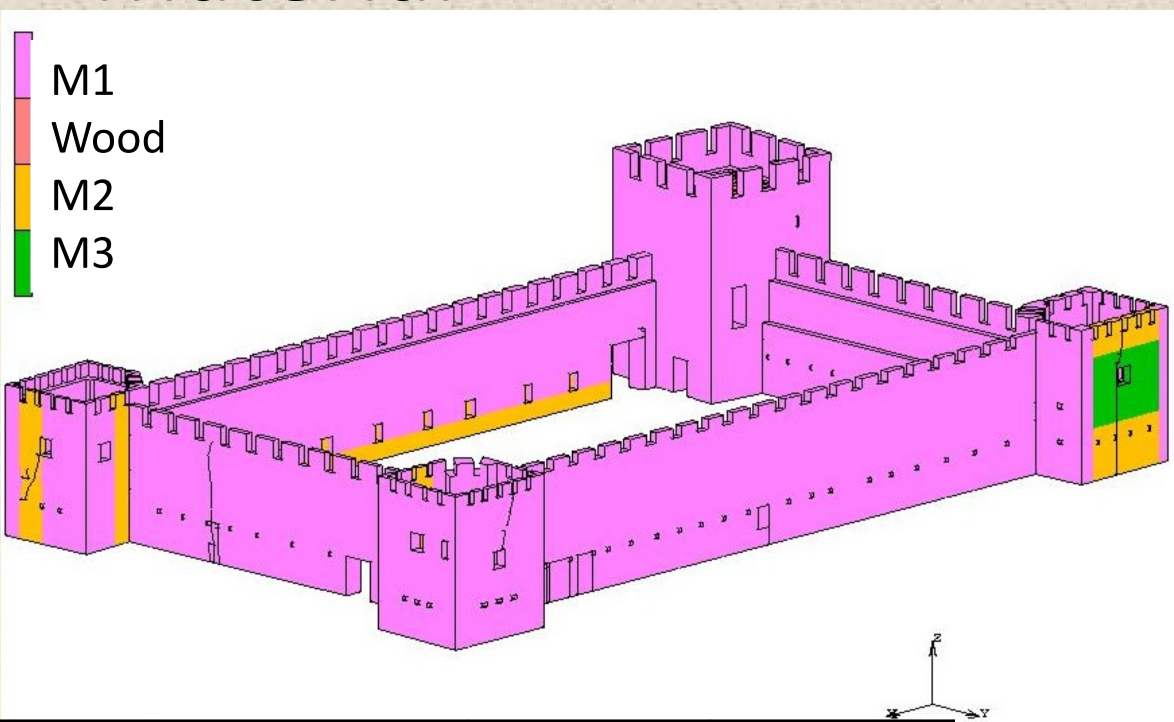
Structural analysis
Finite element models

The model consists of 16743 three-dimensional finite elements (Model 1)

The modelling was based on surveys of existing geometry, history of the monument and interventions have been made, the quality of building materials and subsoil conditions

Structural analysis
Material

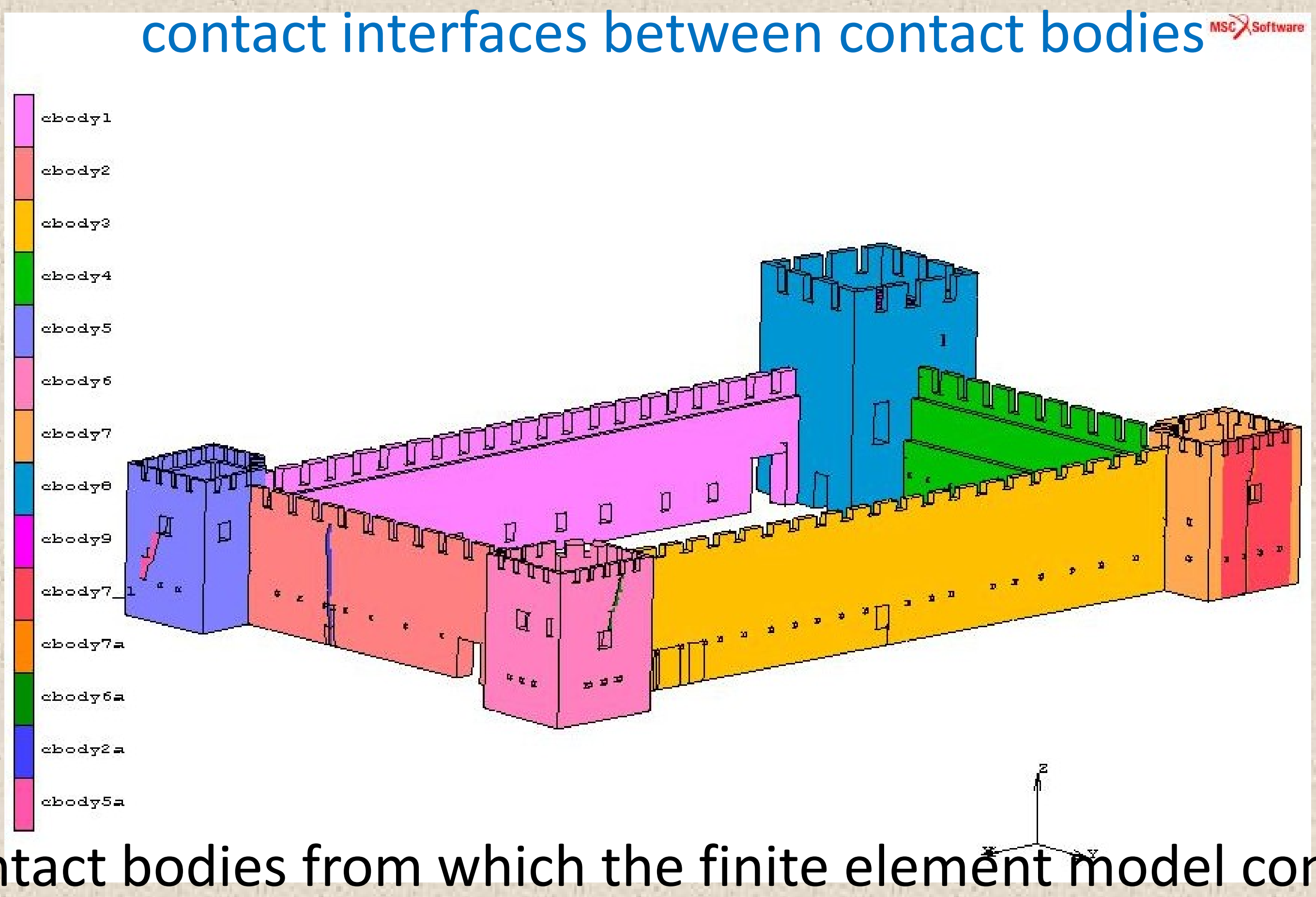
Different materials to specific areas, in order to consider the major structural damages (like cracks, masonry disorganization) (Model 2)



Material	Young's modulus E (GPa)	Yield stress (MPa)	Compressive strength f_{cd} (MPa)	Tensile strength f_{td} (MPa)	Shear strength f_{sh} (MPa)
M1	21.15	3.53	11.75	1.06	4.8
M2	20.36	2.81	11.31	0.7	4.63
M3	14.63	2.70	8.13	0.5	5.95

Structural analysis
Model with contact bodies

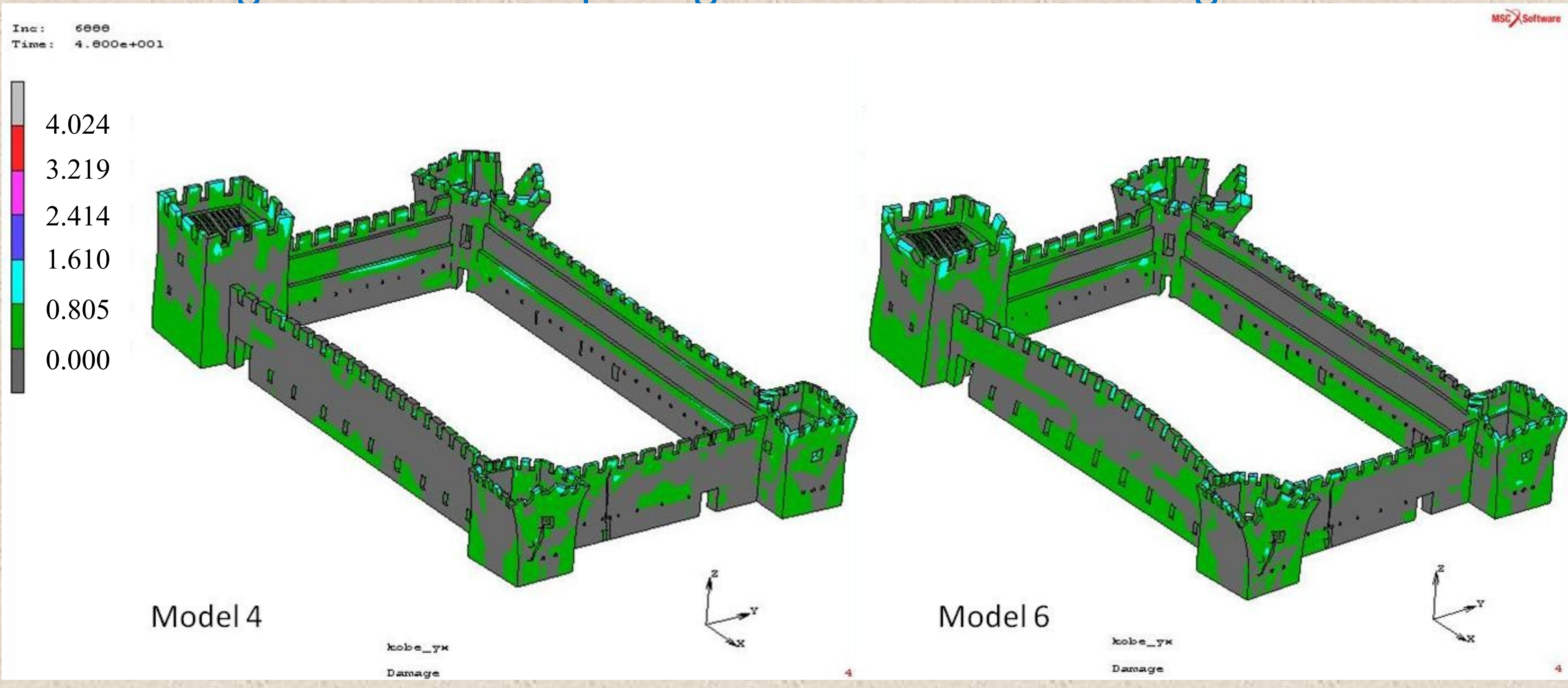
Cracks were simulated by the technique of unilateral contact interfaces between contact bodies



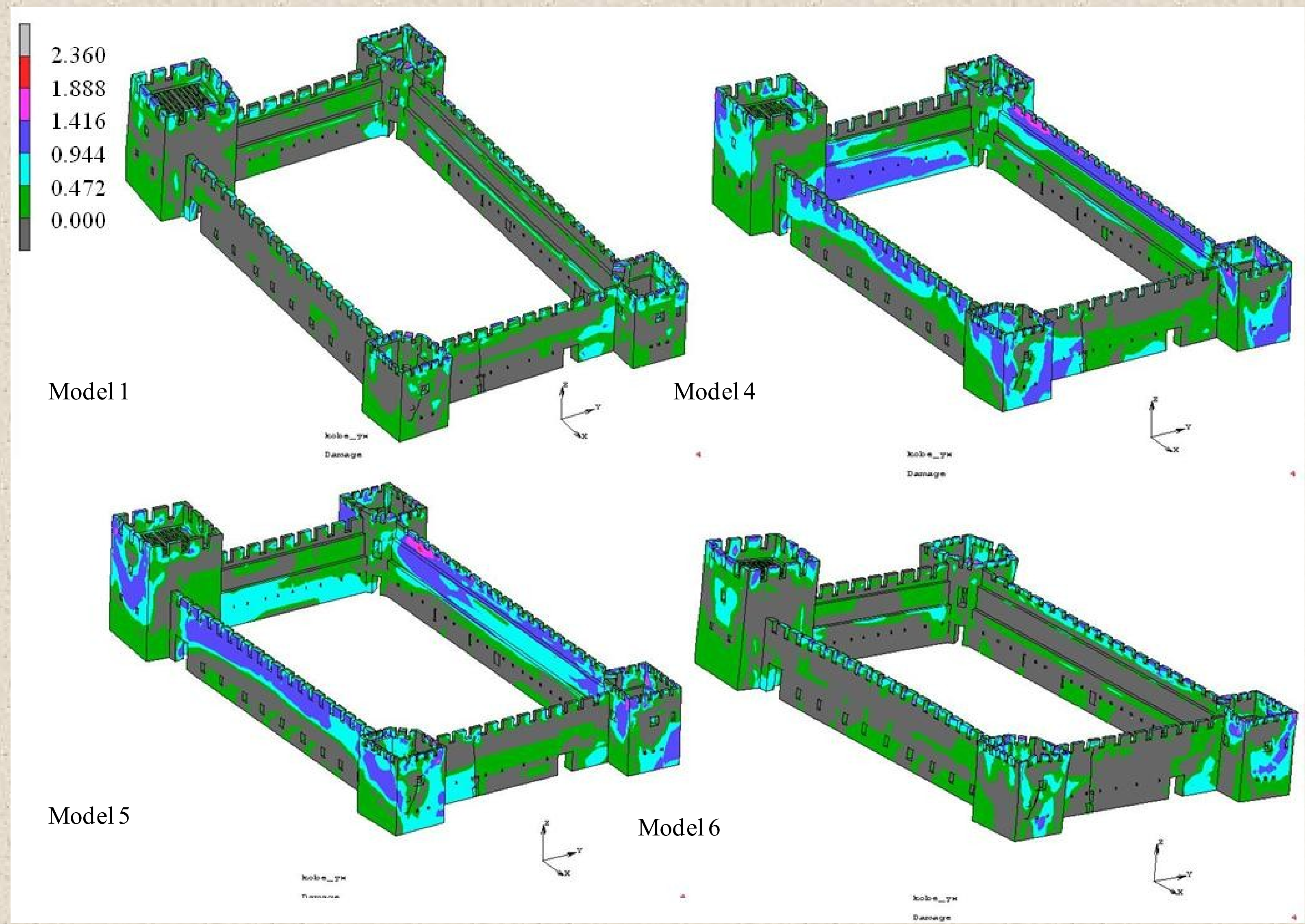
Contact bodies from which the finite element model consist (Model 2).

Structural analysis

Dynamic analysis for earthquake Kobe, Japan, 1995 with magnitude 6.9 and peak ground acceleration 0.8g

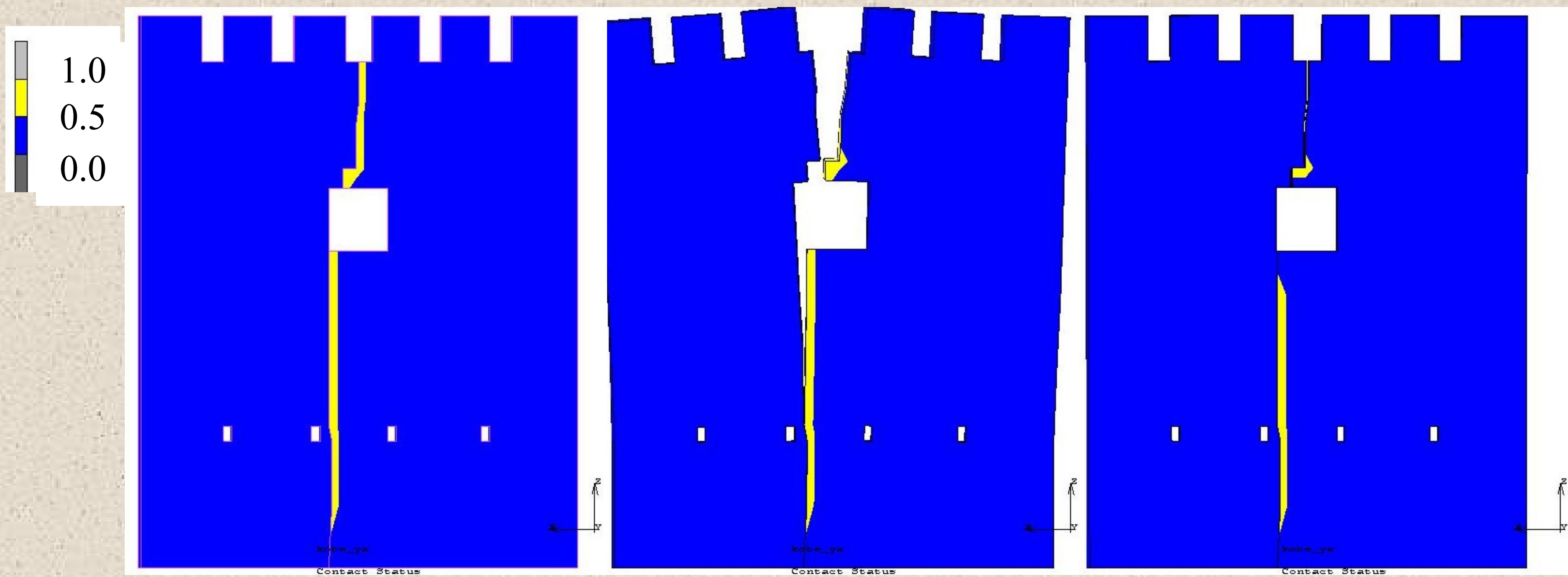


Contour plot of damage index for Models 4, 6 and earthquake Kobe_yx at final time step.



Contour plot of damage index of Models 1, 4-6 and earthquake Kobe_yx at time step 11.5sec.

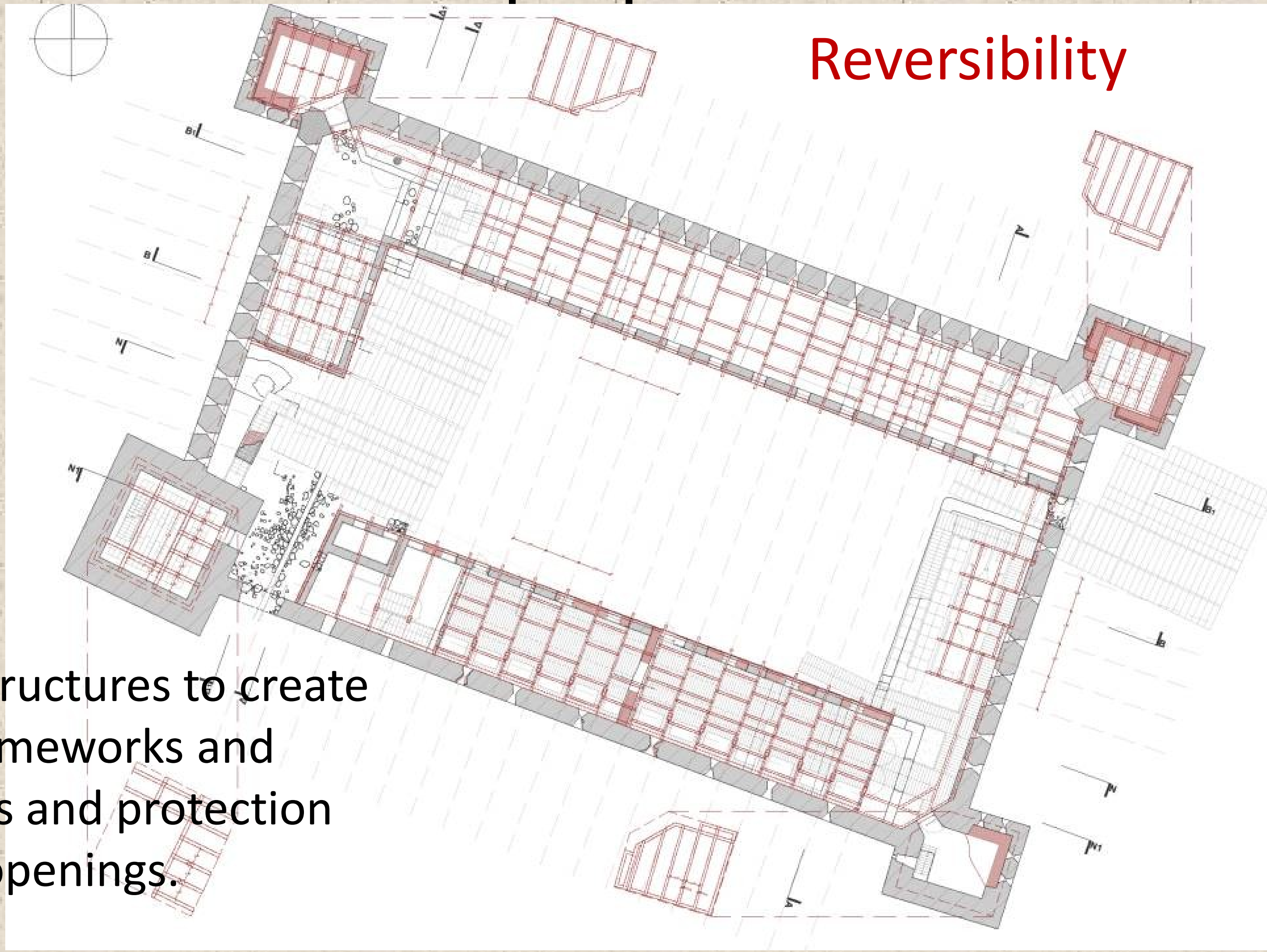
Structural analysis



Time (sec) 0.00 0.115 11.43

Contact status at three time steps of the main crack at the North West tower.

Restoration proposal



Reversibility

Use of wooden structures to create the horizontal frameworks and ironwork for stairs and protection panels of all the openings.

All technical details have been designed as free joints, in a kind of elastic combination between different materials, composing the new totality

Technical University of Crete

Co-funded by the Erasmus+ Programme of the European Union

Development of master curricula for natural disasters risk management in Western Balkan countries

NatRisk

Structural analysis of monuments

Need of cultural heritage protection of natural disasters (like earthquakes)

Structural analysis of existing structures (history, geometry, material, structural faults-damages)

Need of relates scientists to work as group in order to have the interaction of the different subjects which are involved.

10th to 12th July 2017

Technical University of Crete

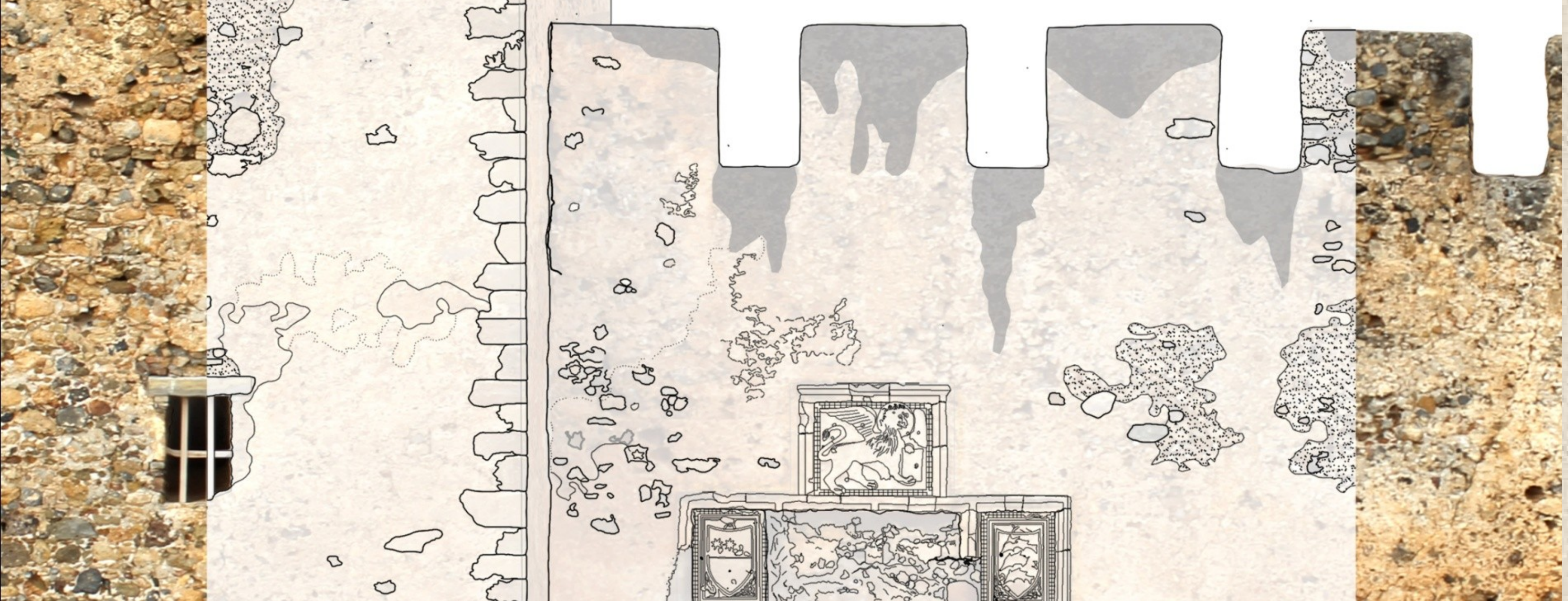
Co-funded by the Erasmus+ Programme of the European Union

Development of master curricula for natural disasters risk management in Western Balkan countries

NatRisk

Thank you

Maria Stavroulaki,
Dr Civil Engineer, Assistant Professor
School of Architecture



10th to 12th July 2017