INTERNATIONAL SYMPOSIUM

SEISMIC RETROFIT OF UNREINFORCED MASONRY HERITAGE CHURCHES IN THE PHILIPPINES

Photo by Raymond Rodolfo

Case study 4: Solutions for URM churches
The Abbey of San Clemente a Casauria, Italy

Sergio Lagomarsino
University of Genoa, Italy

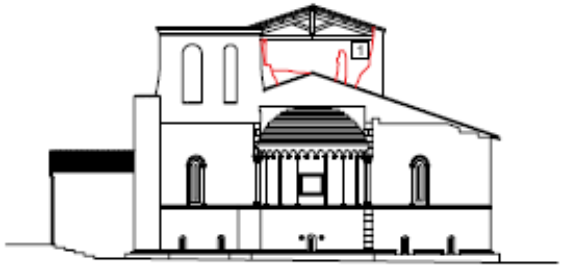
The ABBEY OF SAN CLEMENTE A CASAURIA, Abruzzo, Italy

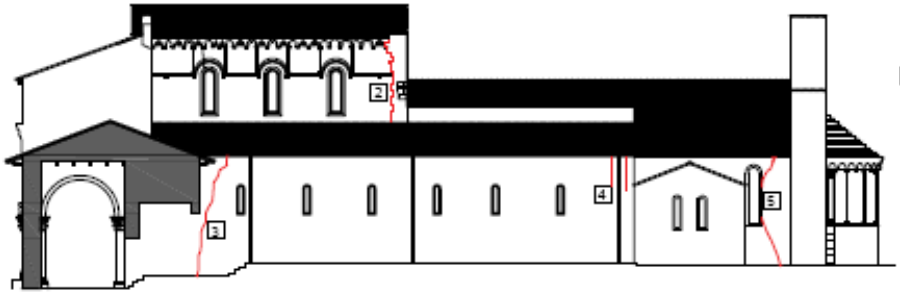
External views

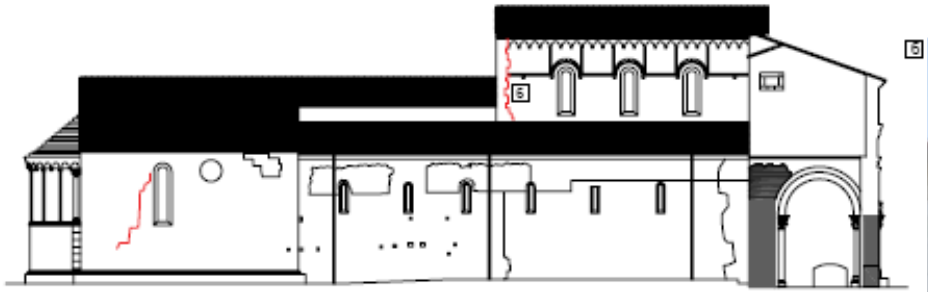
The ABBEY OF SAN CLEMENTE A CASAURIA, Abruzzo, Italy

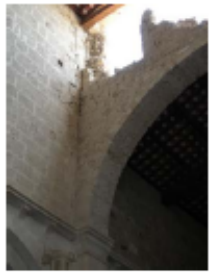
Interior views

Knowledge phase: DAMAGE SURVEY after the L'AQUILA EARTQUAKE 2009





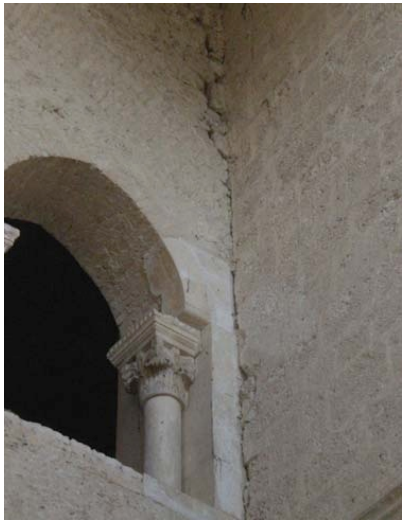




Knowledge phase: DAMAGE SURVEY after the L'AQUILA EARTQUAKE 2009

Collapse of the atop portion wall supported by an arc that separates the nave in two parts.

Severe damage due to: the mechanisms of the triumphal, overturning of the transept walls, overturning of the apse. Damage also in the elements of the roof and in the pillars.



Knowledge phase: STRENGTHENING INTERVENTIONS after the L'AQUILA EARTQUAKE 2009

- Rebuilt of collapsed masonry elements by the same materials: stone and hydraulic lime mortar (in particular the gable in the middle of the central nave).
- General improvement of connections between walls by steel tie-rods, not injected and anchored by external bolts in stainless steel.
- Strengthening of some masonry columns in the nave, whose section was already increased in the past.
- Repair and strengthening of cracks by mortar injections.
- Local repair of timber elements in the roof and slight increase of in-plane stiffness by bracing.

Consultant of restoration and strengthening interventions: Prof. Gianmarco de Felice, University of Rome 3

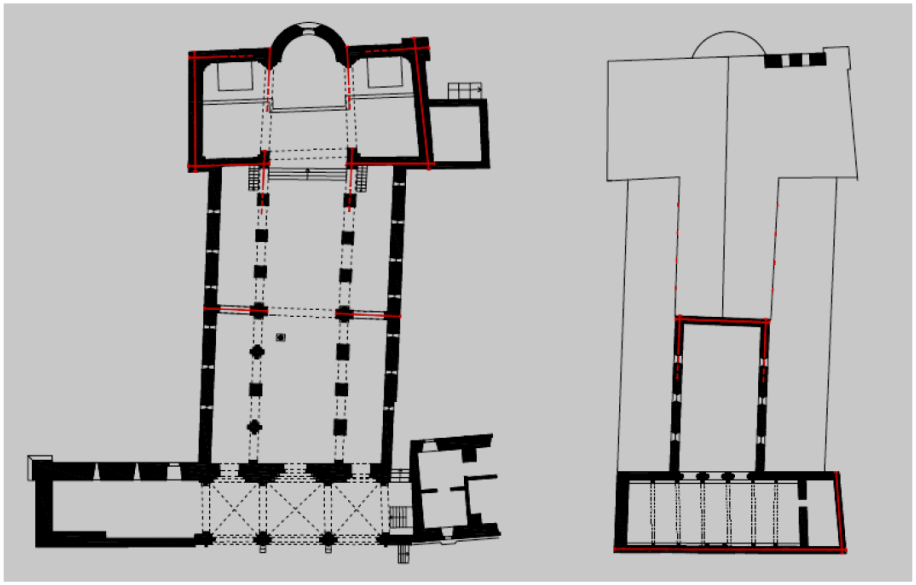
Knowledge phase: STRENGTHENING INTERVENTION after the L'AQUILA EARTQUAKE 2009

Rebuilding of the atop wall collapse - Views from inside and outside

Lime mortar injection of cracks

Artistic heritage restoration

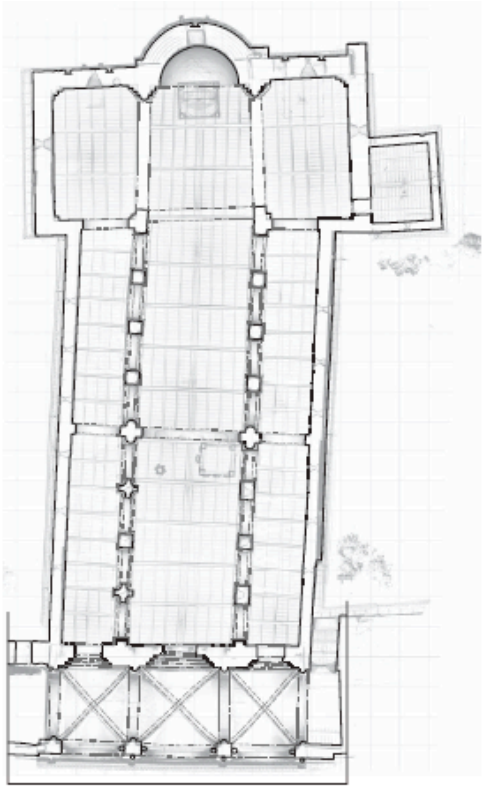
Knowledge phase: STRENGTHENING INTERVENTION after the L'AQUILA EARTQUAKE 2009



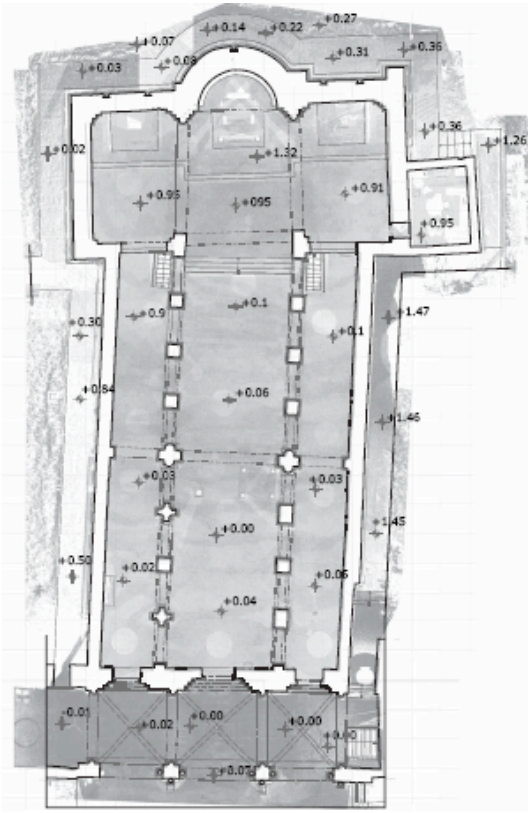
Identification in plan of the new tie-rods (red)

Knowledge phase: GEOMETRIC SURVEY OF THE CHURCH

Performed by laser scanner survey (outside and inside) and topographic survey

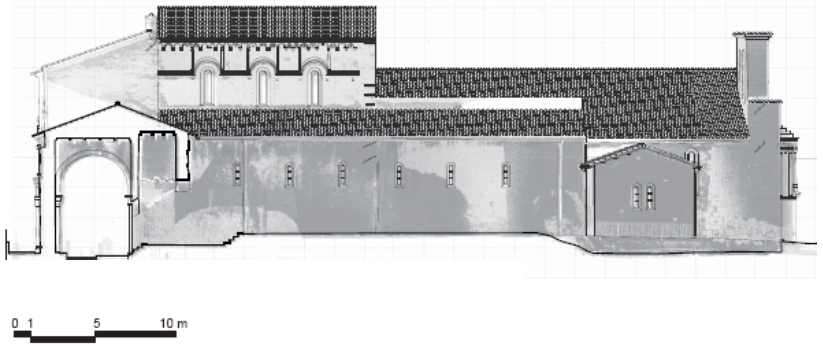


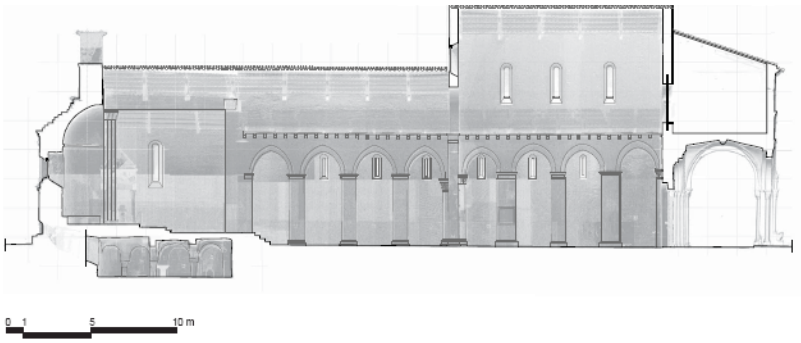
Roof plan



Floor plan

Longitudinal Section





Knowledge phase: HISTORICAL ANALYSIS

Aimed to understanding the church in its architectural and structural parts, through the knowledge of the changes occurred over time, in particular related to the past seismic events.

871 - The abbey was founded by Louis II, grand-grandson of Charlemagne, after a vow made during his imprisonment in the Duchy of Benevento. Initially entitled to the Holy Trinity, it was dedicated to St. Clement when the latter's remain were brought here in 872.;

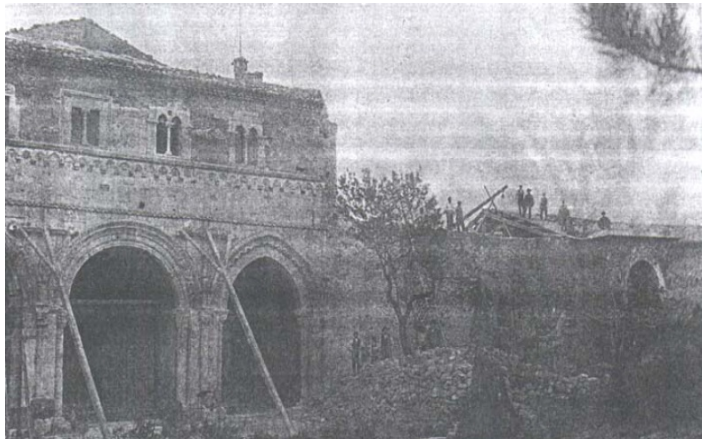
1076 and 1097 - The abbey was plundered several times by the Norman count Malmozzetto;

1105 - The Benedictine abbot Grimoldi promoted the rebuilding of the church. However, the works ended only in the late 12th century under abbot Leonate;

1231, 1348, 1456 – Earthquakes that hit the structure;

1915 – Avezzano earthquake, destruction of the convent and severe damage to the Church.

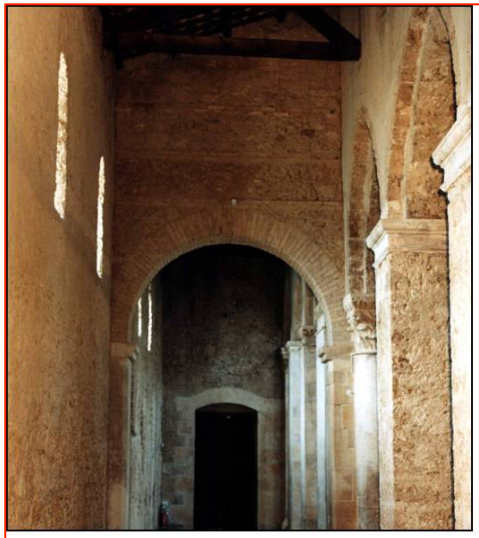
High-Relief on the façade, the church at the time of Abbot Leonate (1778)

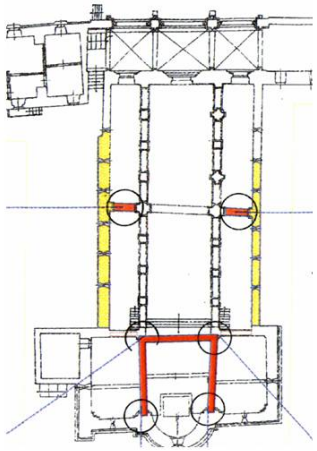


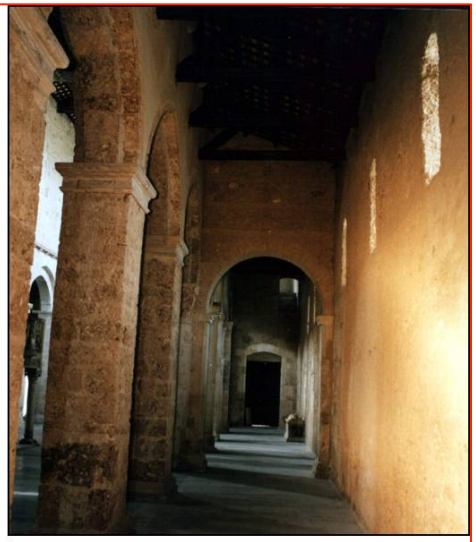
The abbey after the earthquake of 1915

Knowledge phase: HISTORICAL ANALYSIS

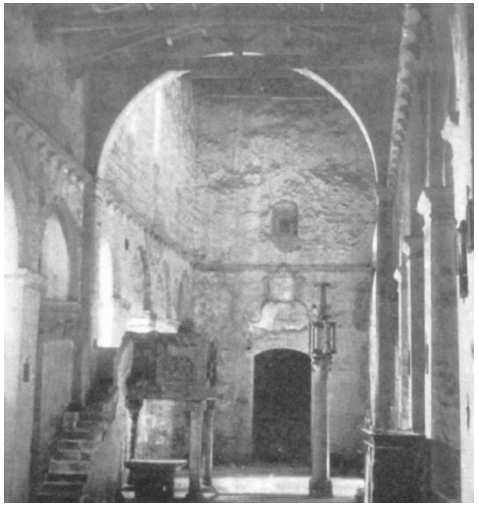
Significant structural intervention - Gavini 1919

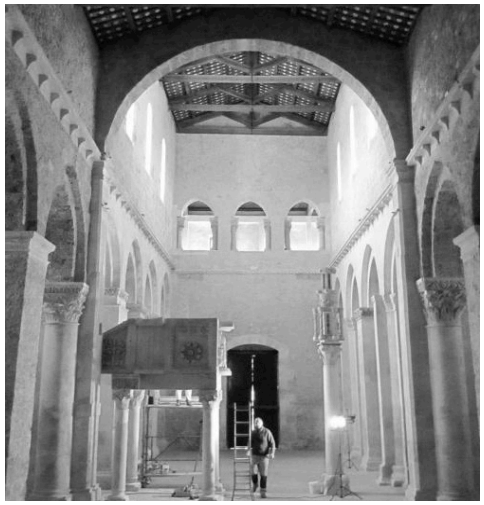






In the area of the transept two walls were demolished, inserting the reinforced concrete beams

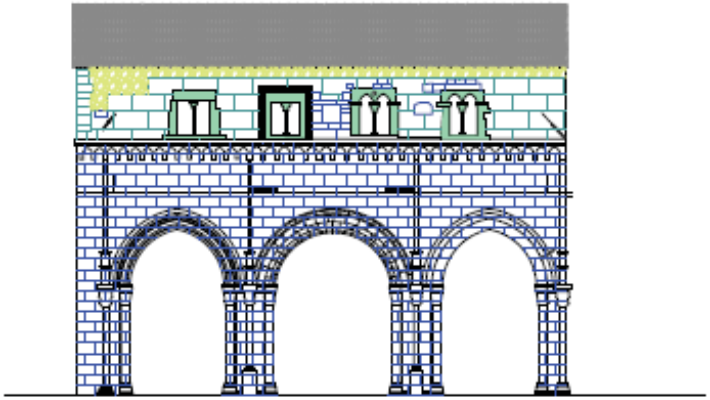


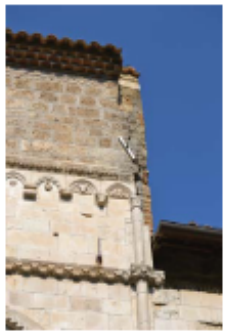


Reconstruction of the loggia in the backside of the façade

Knowledge phase: TECHNOLOGICAL SURVEY OF THE CHURCH - MATERIALS

Facade





Apse

LEGENDA

- MURATURA INTERVENTO 2010 [1]
- RIVESTIMENTO IN PIETRA GENTILE [2]
- MURATURA A VISTA SI IPOTIZZA 1600 [3]
- MURATURA INTONACATA SACRESTIA [4]
- MURATURA IN BLOCCHI SQUADRATI A VISTA 1400 [5]
- MARMO [6]
- MURATURA IN PIETRAME DISORDINATO [7]
- BLOCCHI IN PIETRA DELLA SEDUTA [8]

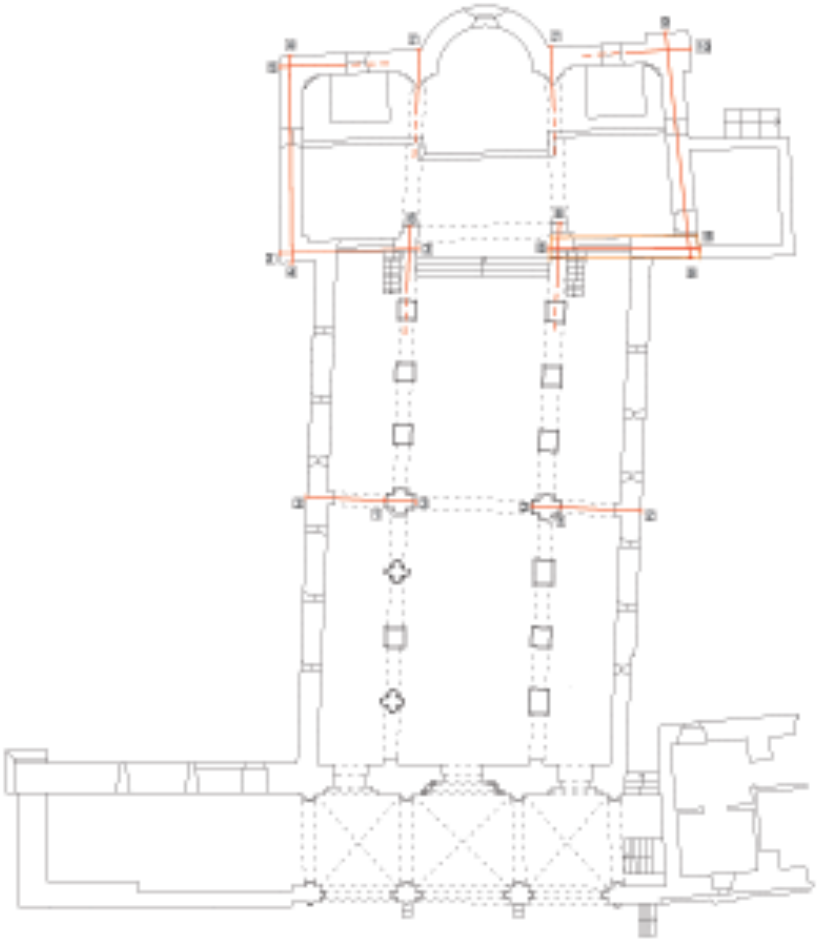
Knowledge phase: TECHNOLOGICAL SURVEY OF THE CHURCH – Constructive details of the walls

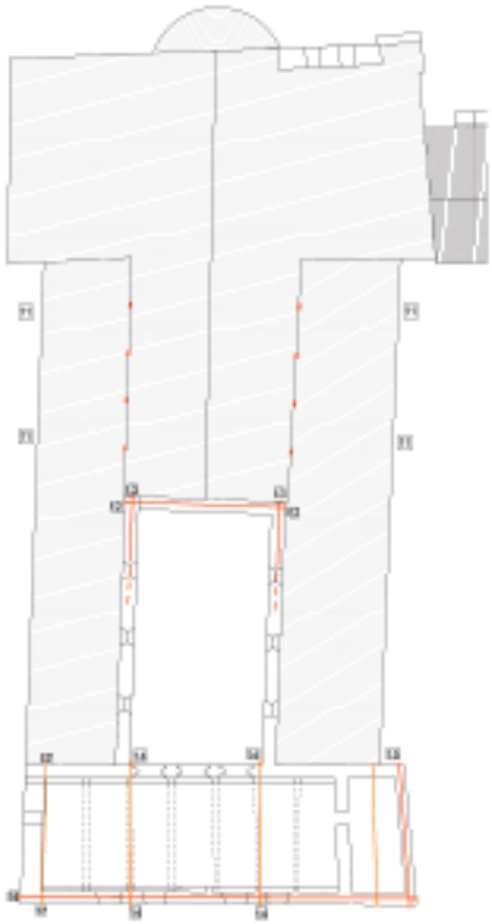
- Connection between the walls;
- Presence of tie-rods and ring beams.

The appearance of the damage occurred at the intersection of walls is a very important indicator for the assessment of the effectiveness of connections.

Knowledge phase: TECHNOLOGICAL SURVEY OF THE CHURCH – Constructive details of the walls

- Presence of tie-rods





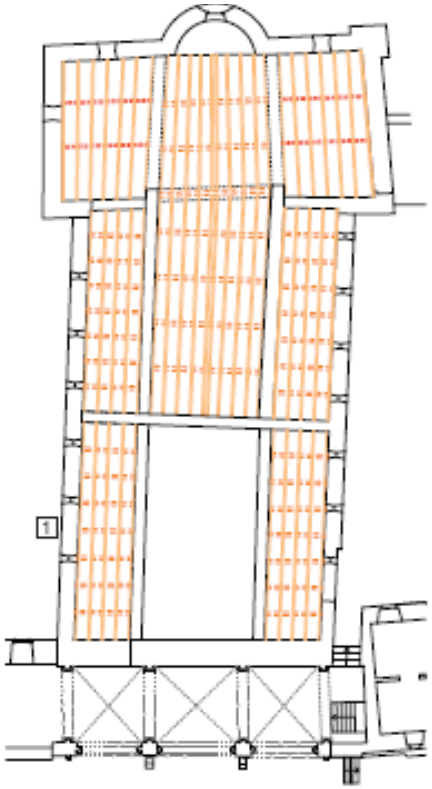
Red: New Tie-rods inserted after L'Aquila earthquake

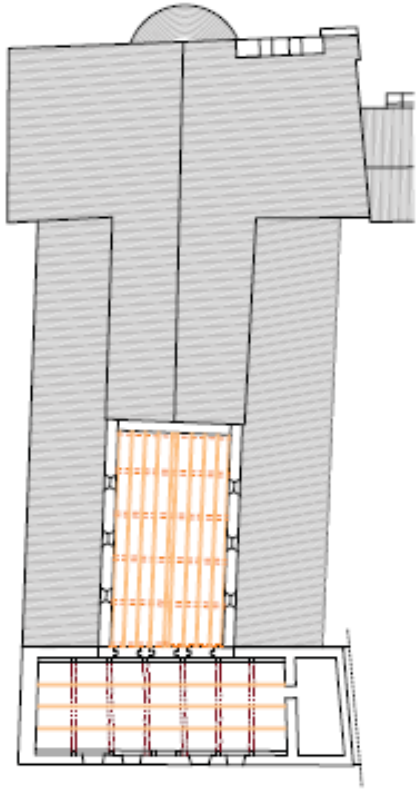
Orange: Old tie-rods

Knowledge phase: TECHNOLOGICAL SURVEY OF THE CHURCH – Constructive details of diaphragm

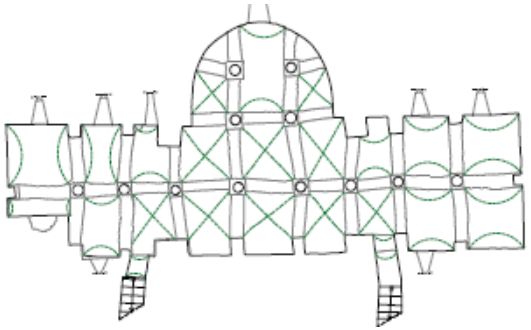
Identification of the horizontal diaphragms for each parts of the church.

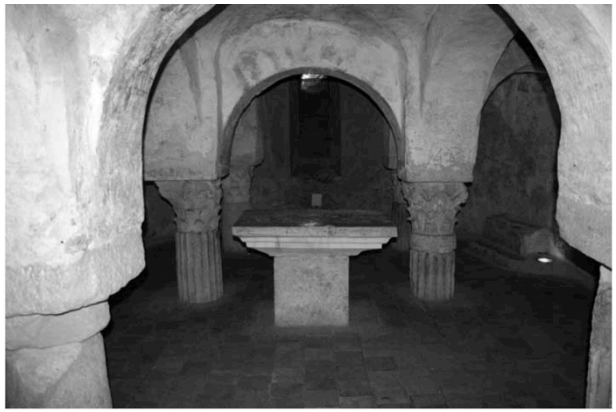
Timber roof in the Nave and aisles





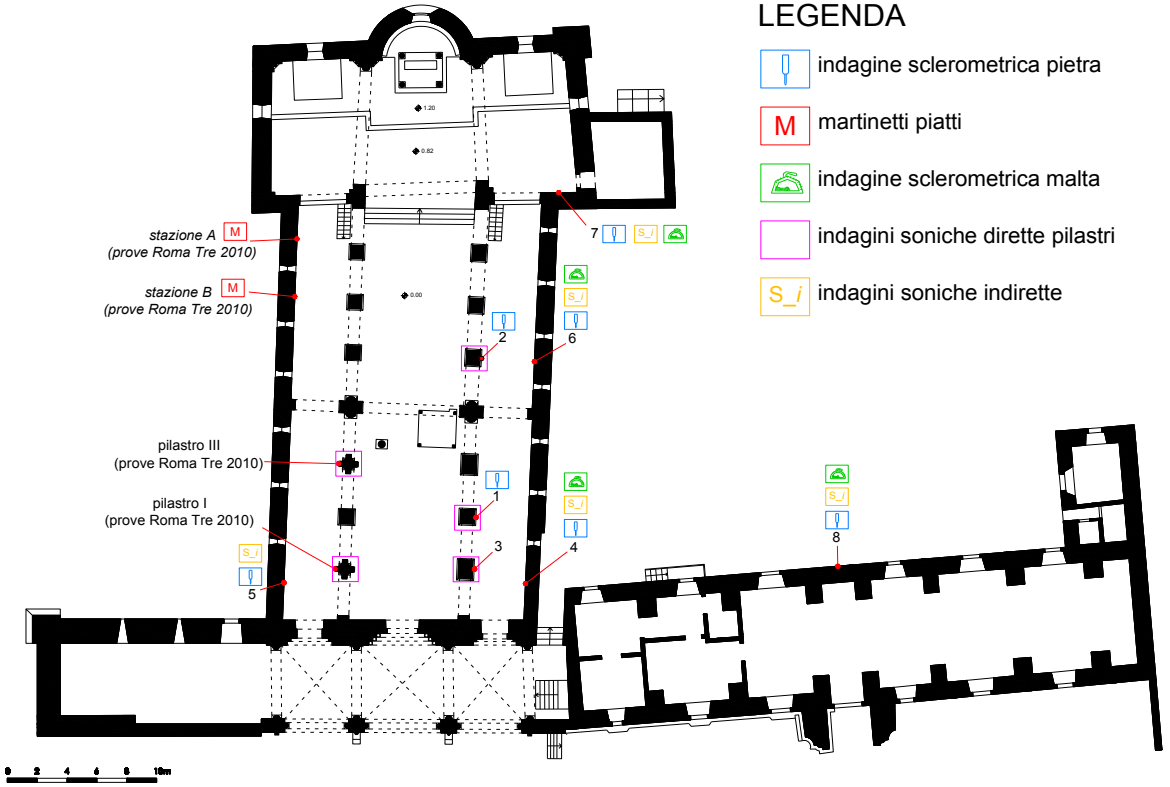
Stone vaults in the Crypt



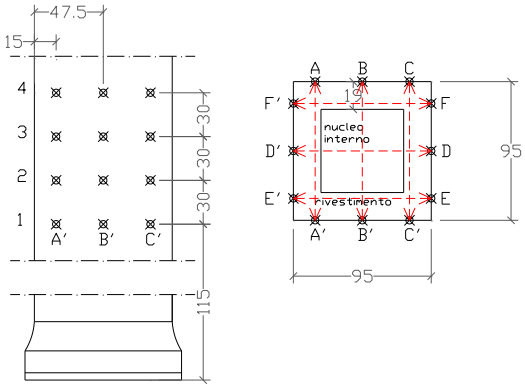


Knowledge phase: DIAGNOSTIC TESTS for the MECHANICAL CHARACTERIZATION OF MATERIALS

Definition of the tests aimed to the identification of masonry types



Rebound test



Sonic tests

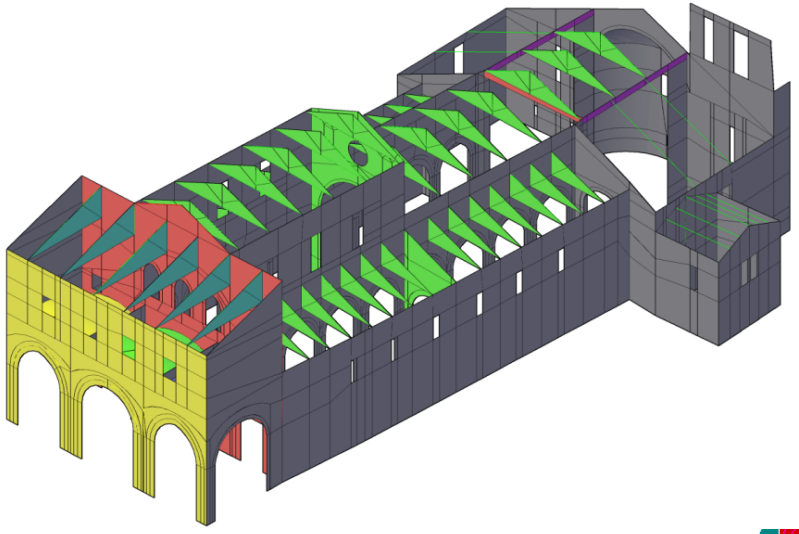
SEISMIC ASSESSMENT

The seismic response of the church has been analyzed through:

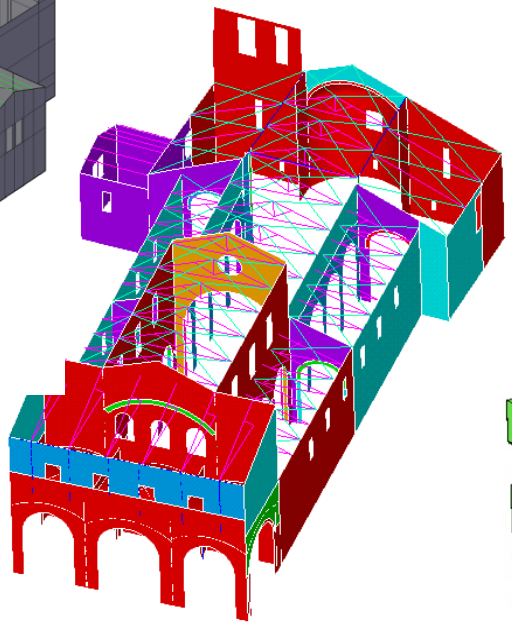
I. The decomposition of the church into significant **MACROELEMENTS**

II. Linear analysis through **3D FINITE ELEMENT MODEL**, aimed to define the distribution of the seismic action among the macroelements, due to their relative stiffness

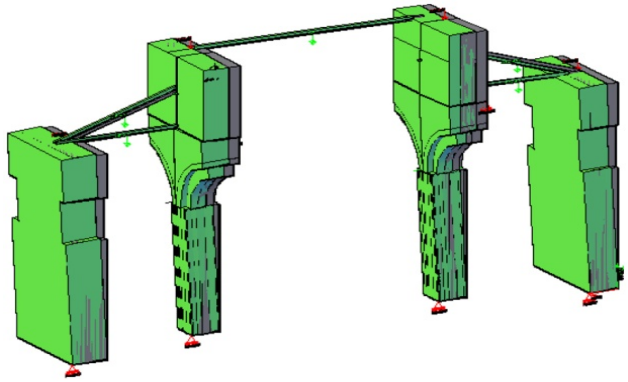
III. Nonlinear analyses for each macroelement (**SEM o MBM model**)



Geometric model



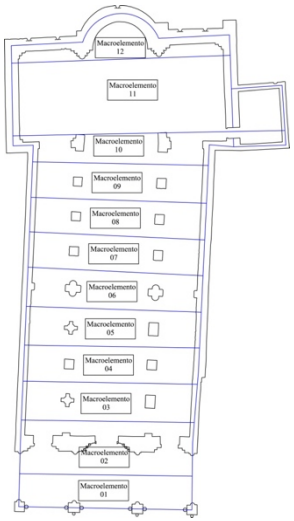
FEM model



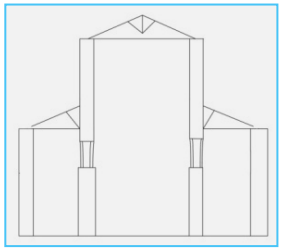
Macroelement model

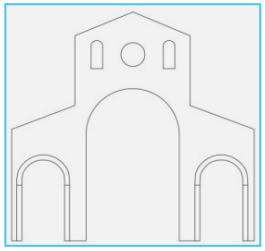
I. Identification of the N macroelements of the church

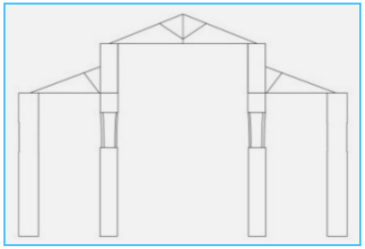
Analysis considering two independent directions: transversal and longitudinal seismic response

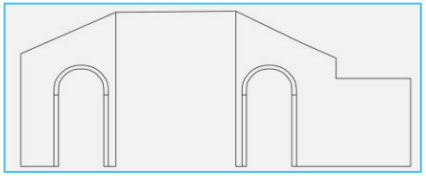


Transversal response

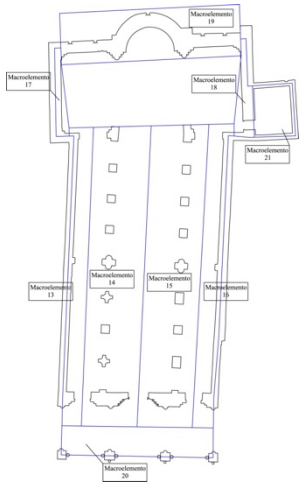




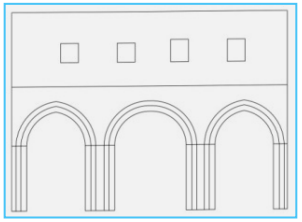


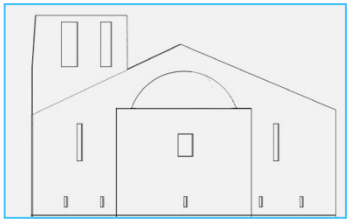


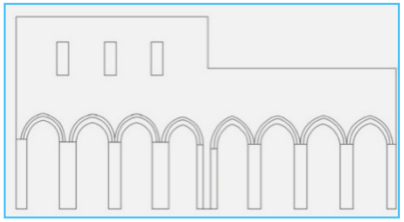
NONLINEAR KINEMATIC ANALYSIS
NONLINEAR STATIC ANALYSIS



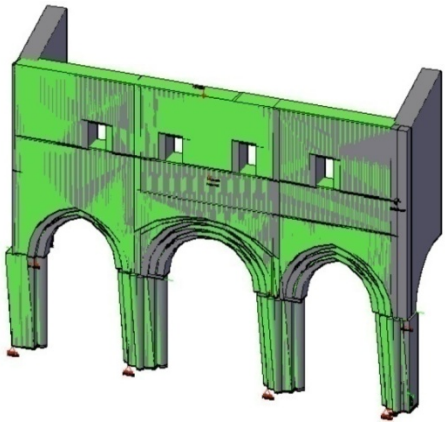
Longitudinal response

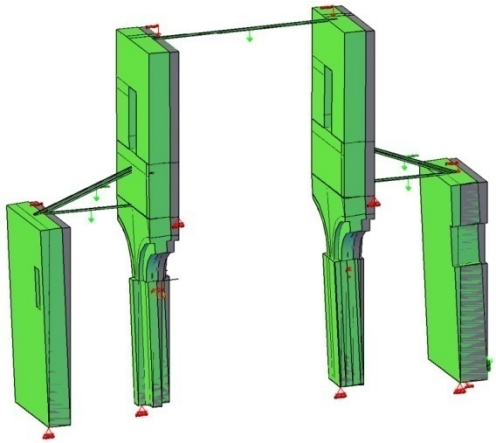


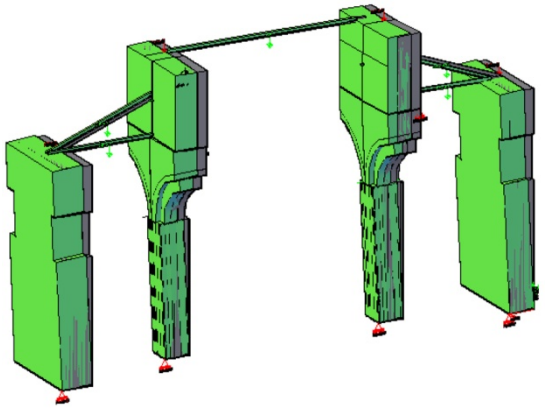


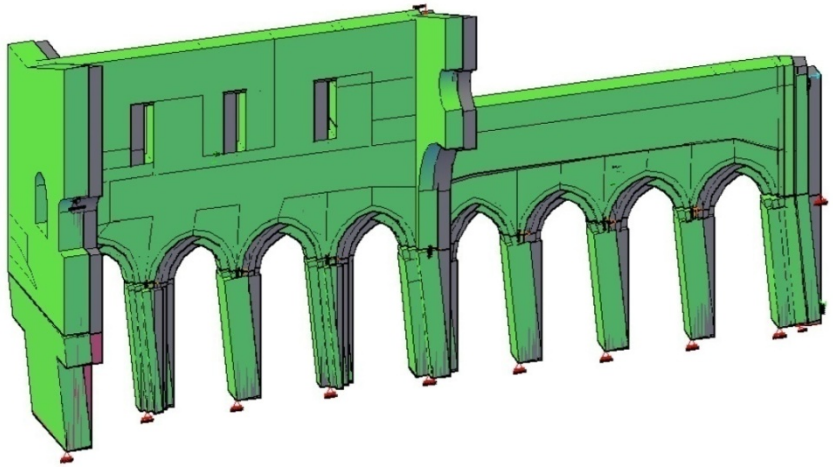


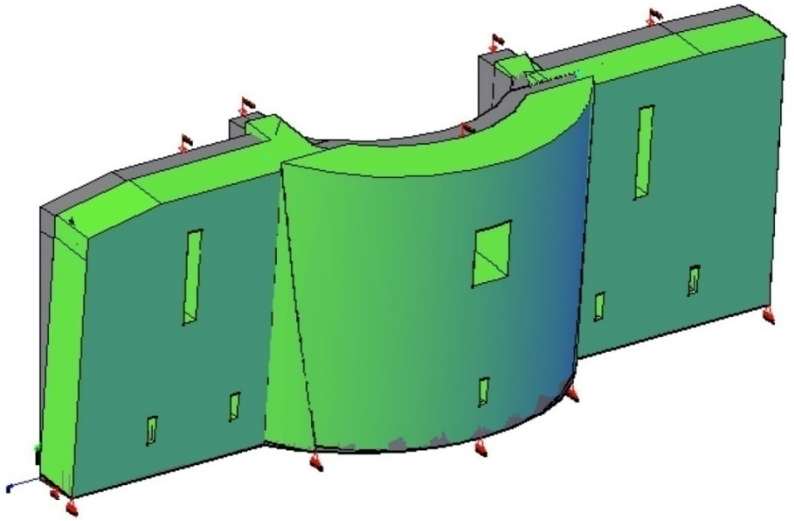
I. Identification of the N macroelements of the church







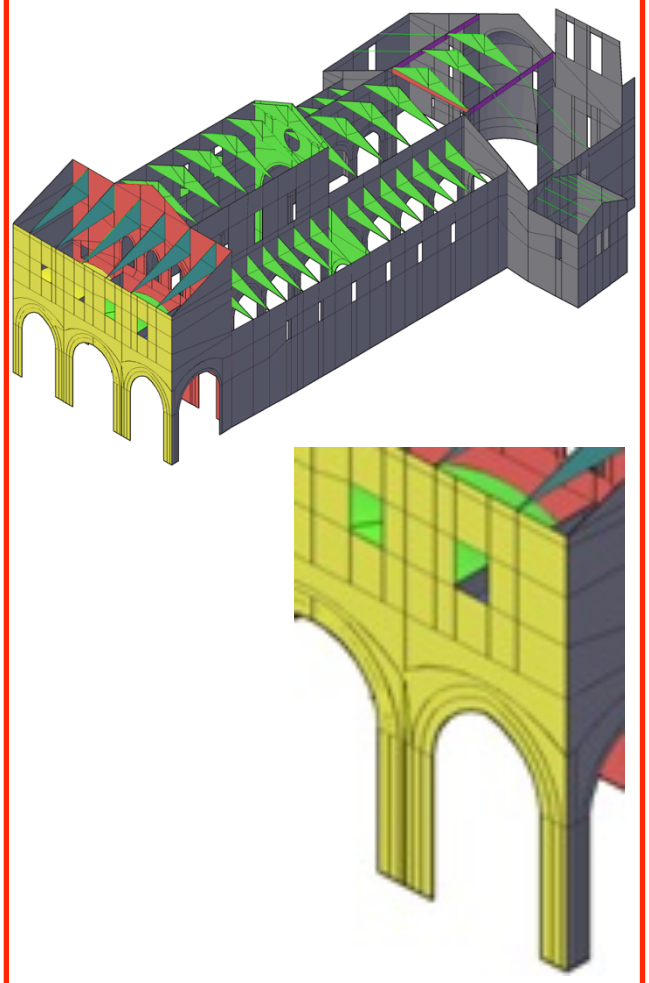




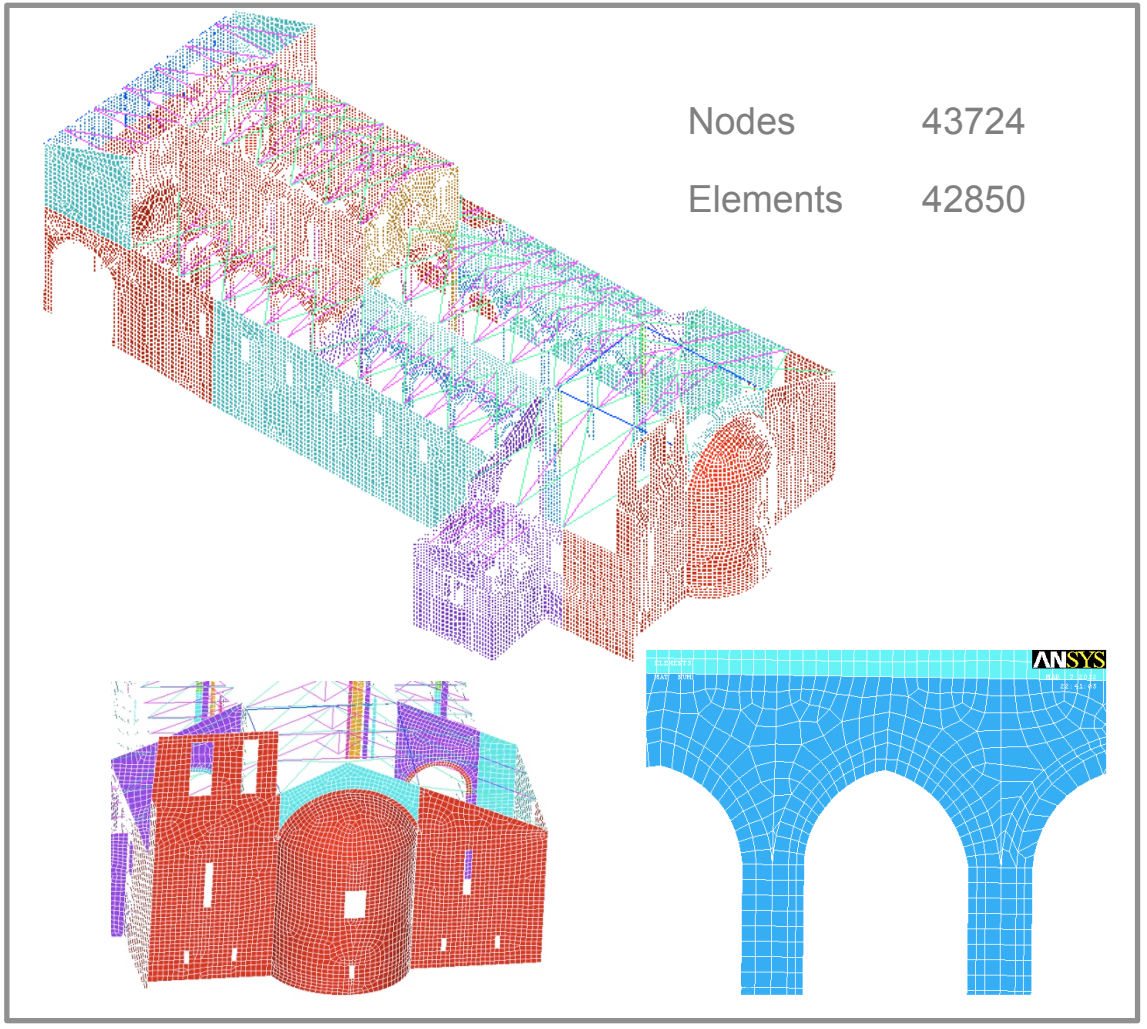
II. Linear analysis static and dynamic on the 3D finite element model

The complexity of masonry buildings suggests the use of the finite element method, as theoretically able to model the response of complex geometries, in conditions of maximum generality in the constraints and loads.

Geometric Model



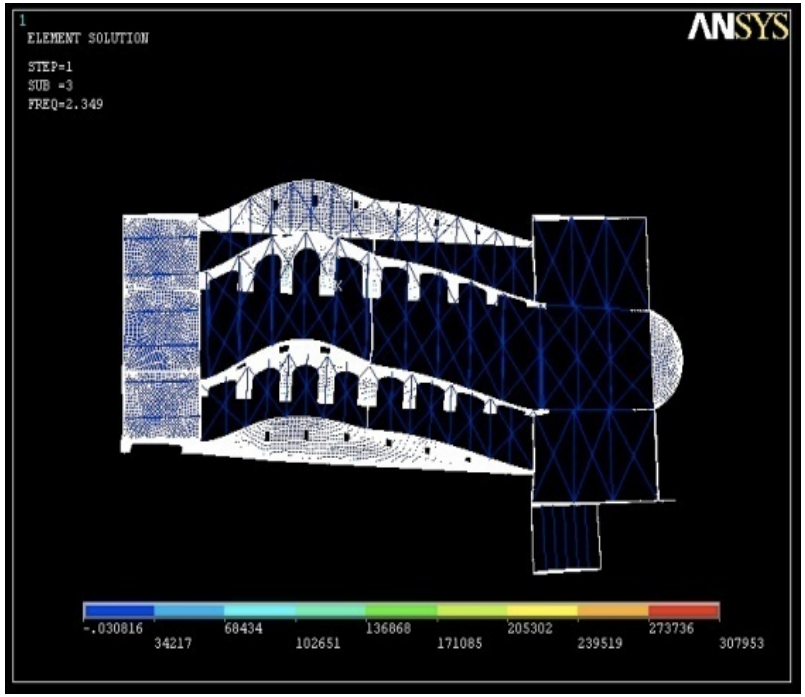
Finite Element Model



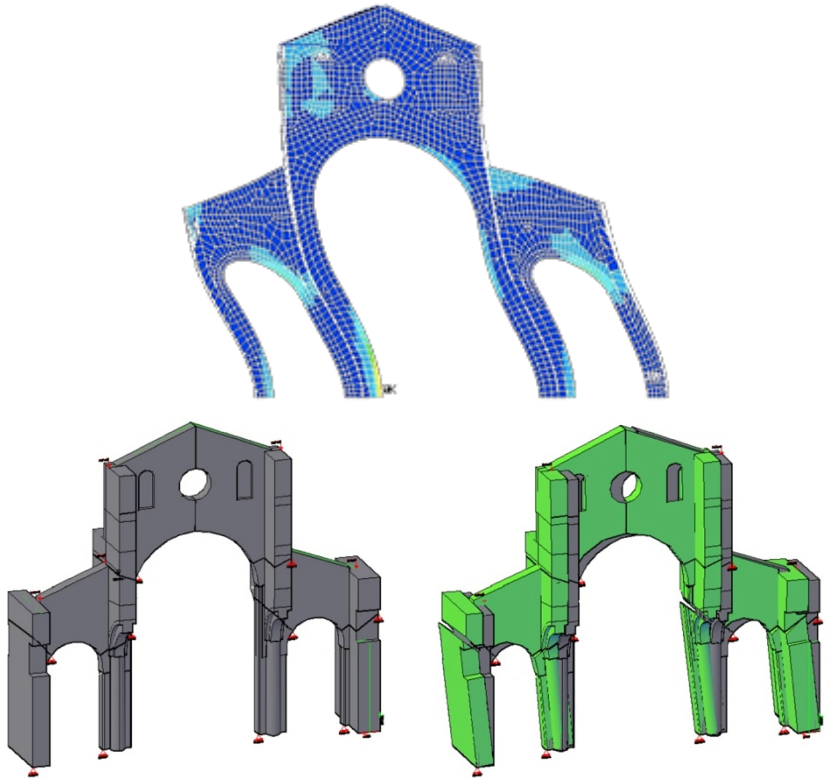
II. Linear analysis static and dynamic on the 3D finite element model

Aimed to:

- ❑ Comprehension of the global behavior of the structure, especially its dynamic response;
- ❑ Identification of the most vulnerable macroelements;
- ❑ Computation of macrolements stress in order to defining the loads distribution among the macroelements;
- ❑ Support for the identification of mechanisms to analyze for each macroelement.



ES. Fundamental mode in X direction
(Mass participant 38%)



Identification of the collapse mechanism

II. Linear analysis static and dynamic on the 3D finite element model

❑ Definition of the loads distribution among the macroelements.

Through the computation of the corrective coefficient α_n which allow to vary the masses in the nonlinear analysis of each macroelement. Two different loads distributions are considered.

$$\alpha_{1,n} = \frac{F_{x(y)}}{F_z}$$

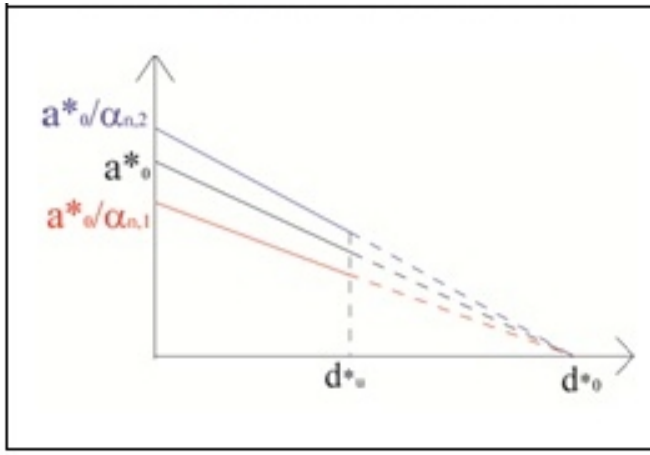
Proportional to the static mass (following a linear static analysis with gravitational and horizontal acceleration).

$$\alpha_{2,n} = \frac{F_{n,x(y)}}{F_z} \frac{\sum_n F_z}{\sum F_{n,x(y)}}$$

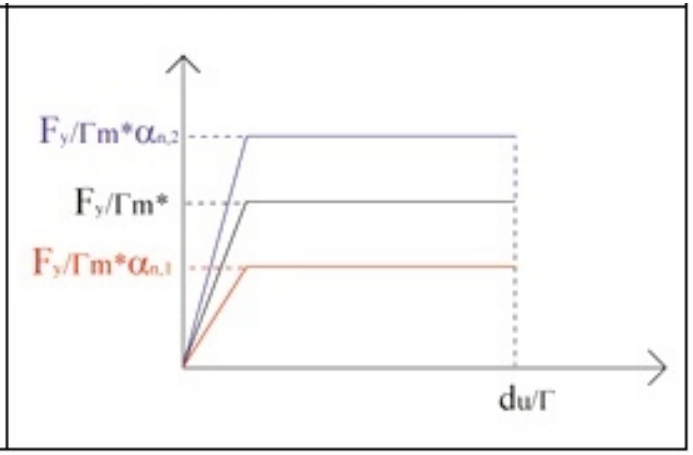
Proportional to main vibrational modes, with a number of modes representative of the dynamic response of the structure (following a linear dynamic analysis)

Sd-Sa curves of the 1GDL, varied by the coefficients α_n to take into account the effect of the repartition.

NONLINEAR KINEMATIC ANALYSIS



NONLINEAR STATIC ANALYSIS

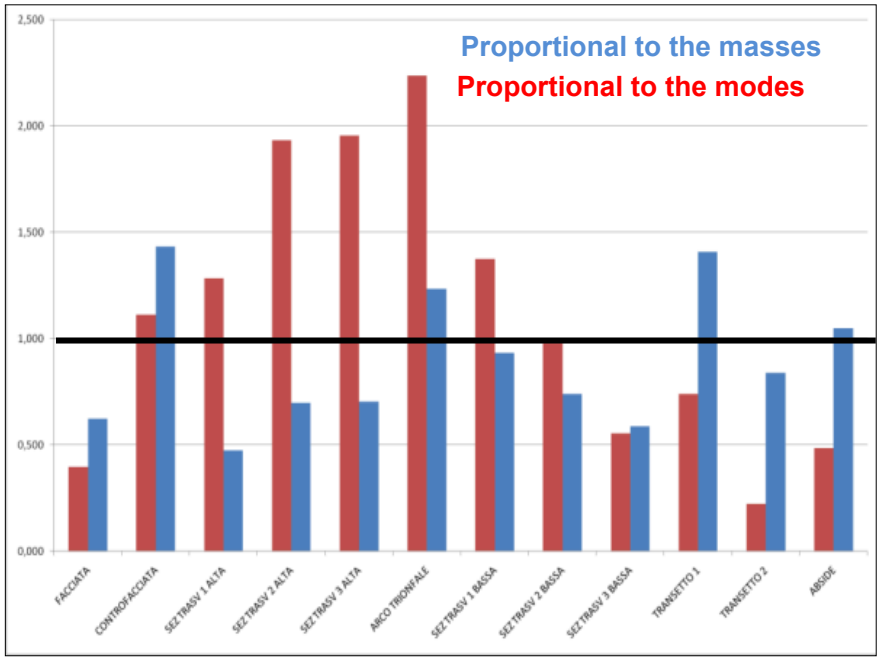


II. Linear analysis static and dynamic on the 3D finite element model

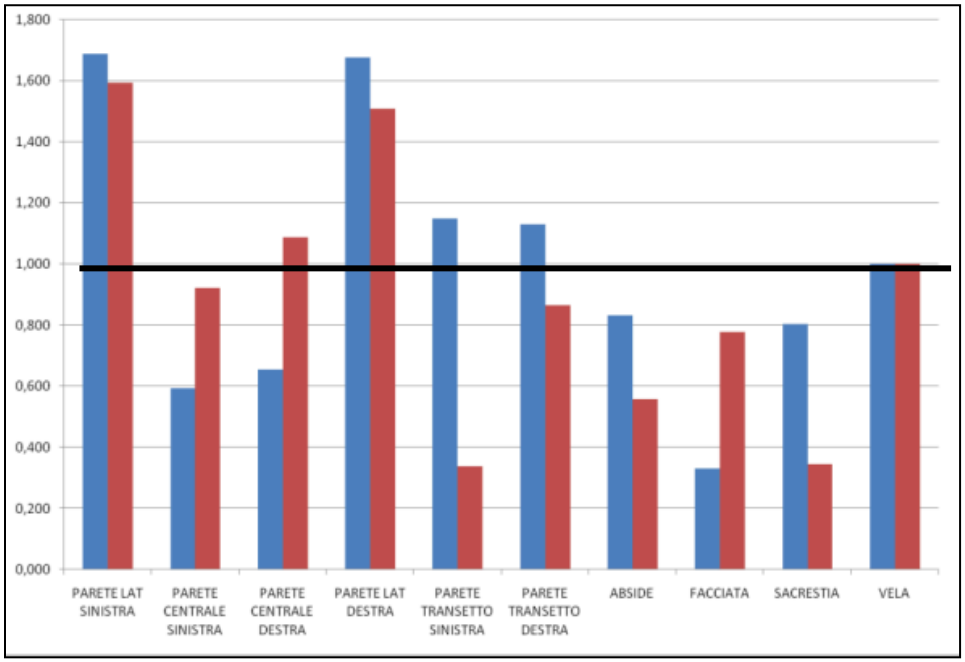
At the end of this phase are defined the corrective coefficient α_n for the loads distribution among the macroelements.

Coefficients greater than 1→ the macroelement takes more seismic action than the results which would be achieved considering only the masses which affect the specific macroelement, regardless of the distribution of seismic action;

Coefficienti below 1 → the response of the macroelement takes advantage from the repartition.



Transversal direction

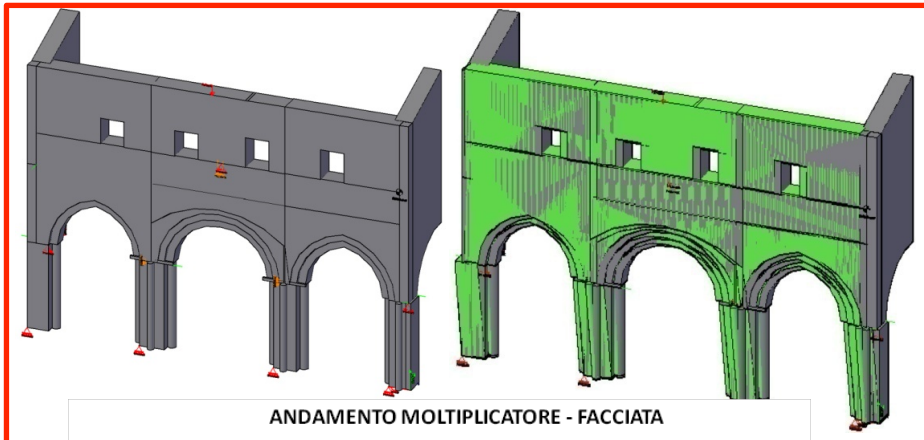


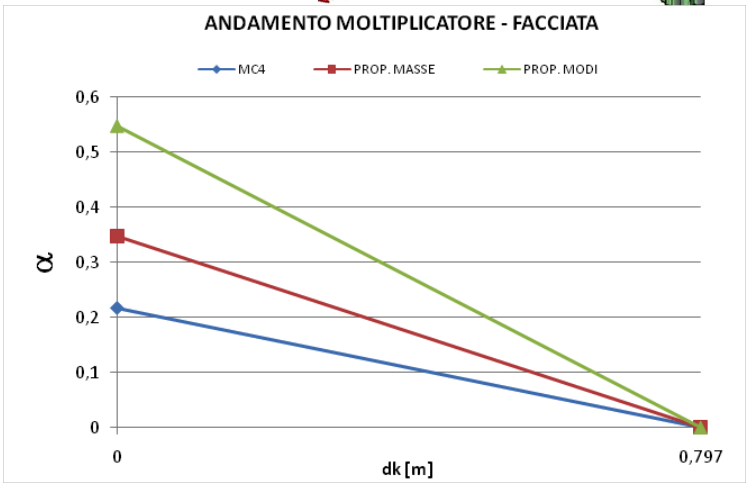
Longitudinal direction

III. Nonlinear analyses for each macroelement

Aimed to the defintion of the capacity curves of the macroelements until the collapse and comparison with the seismic demand. The seismic analysis was perfomed in the ambit of ***"Performance-based assessment"***. In particolar, varying the seismic behaviour of the macroelemente, the capacity curve is obtained with the following models:

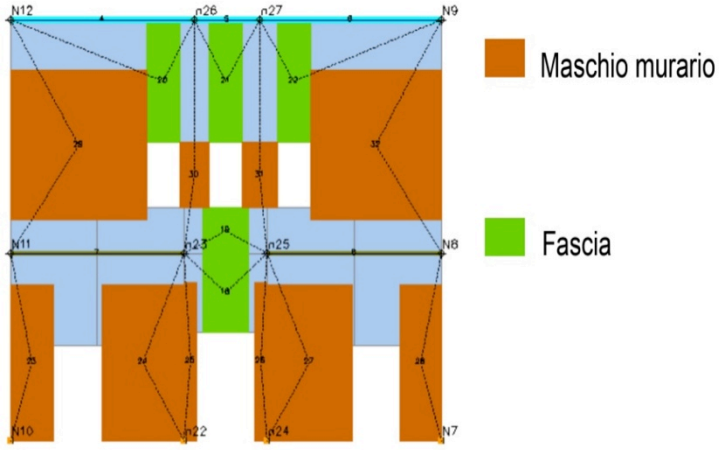
Macro-Block Model

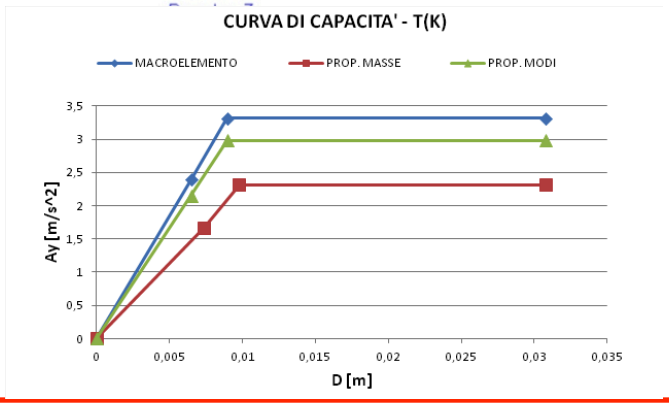




Software: Mc4Loc (Mc4software).

Structural Element Model



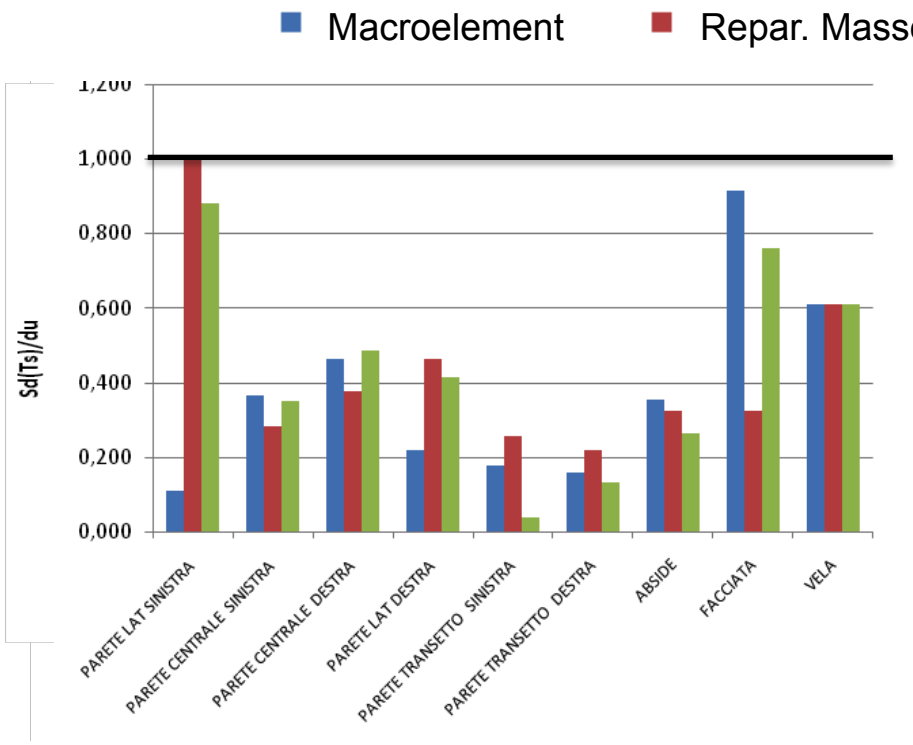


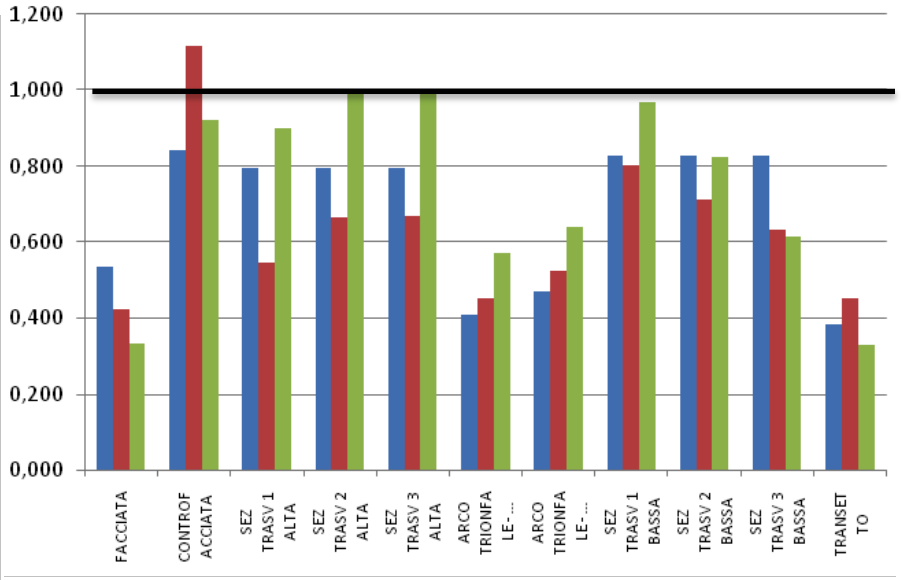
Software: 3Muri ® release 5.0.2 (S.T.A. DATA s.r.l.), developed by the University of Genoa.

III. Nonlinear analyses for each macroelement

For each direction and the Limist State, Life Safety, the graphs show the comparsion between the Demand and Capacity for the different consigurations:

- ✓ “Macroelement”: Given only the loads and the masses of the specific macroelement;
- ✓ “Repar. Masses”: Given the repartition of the seismic action determined by the force distribution proportional to the masses on the global model;
- ✓ “Repar. Modes”: Given the repartition of the seismic action determined by the force distribution proportional to the main modes.





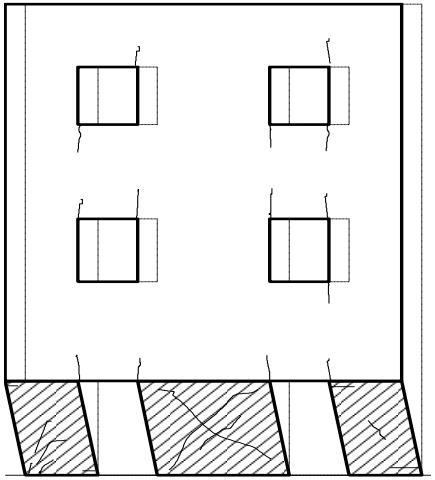
The few values greater than 1 entail the demand exceed the capacity, this is due to the strengthening intervention.

CONCLUSIONS
REHABILITATION STRATEGIES

- CONSERVATION WITHOUT INTERVENTIONS
  - the building is safe
  - limitation of use (revision of performance requirements)
  - interventions can be postponed (or incremental actions)
- DESIGN OF REHABILITATION INTERVENTIONS
  - prevention of local mechanisms (connections)
  - seismic improvement of global behavior
    - ✓ increasing diaphragms stiffness (from macroelements to global behavior)
    - ✓ reducing plan irregularities and torsional effects (bracing, seismic joints)
    - ✓ improving seismic capacity: stiffness/strength, displacement capacity, both (take care of collapse mechanisms and ductility)
- STRUCTURAL HEALTH MONITORING & MAINTENANCE
  - model updating
  - validation of interventions

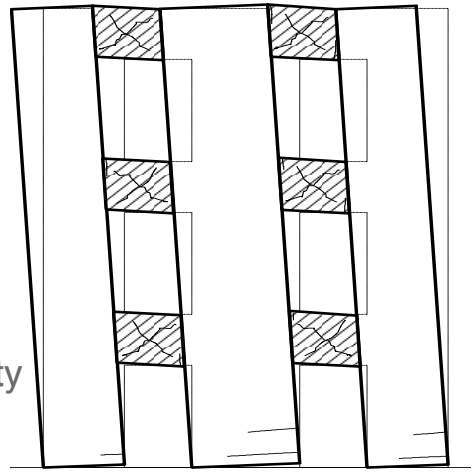
Resilience-Based strengthening of masonry buildings

Improve the displacement capacity by localizing damage in spandrels



STRONG SPANDRELS & WEAK PIERS

- Low ductility
- Irreparable damage



WEAK SPANDRELS & STRONG PIERS

- High displacement capacity
- Easy repairable damage