THE PROTECTION OF MONUMENTS UNDER SEISMIC ACTIONS
Thessaloniki – Novembre 3-5, 2011

Guidelines for assessment and protection of monuments in seismic areas

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Safety and conservation of historical buildings

Ancient masonry buildings were realized by the RULES OF ART, based on an empirical knowledge of the structural behaviour; this trial and error process took into consideration mainly static actions. Earthquakes have always caused serious damage to masonry buildings (Local Seismic Culture):

High seismicity areas - PREVENTION AWARENESS

Moderate seismicity areas - REPAIR AND STRENGTHENING

In the second half of the XIX century, structural analysis and safety checks started to be used for the design of buildings, in place of the empirical rules. In the same period there was a transition from masonry to reinforced concrete buildings (or steel structures), which can be analysed as linear elastic frames.

After the main earthquakes at the beginning of the XX century (Messina 1908, etc.), new technologies were adopted for masonry buildings (confined masonry) and r.c. elements were used also for the strengthening. Reinforced concrete was used also for monuments, according to the restoration charter of Athens (1931). In Italy, in the first half of the XX century many monuments were strengthened by invasive interventions.

MESSINA EARTHQUAKE (1908)

The first seismic code in Italy was issued in 1909

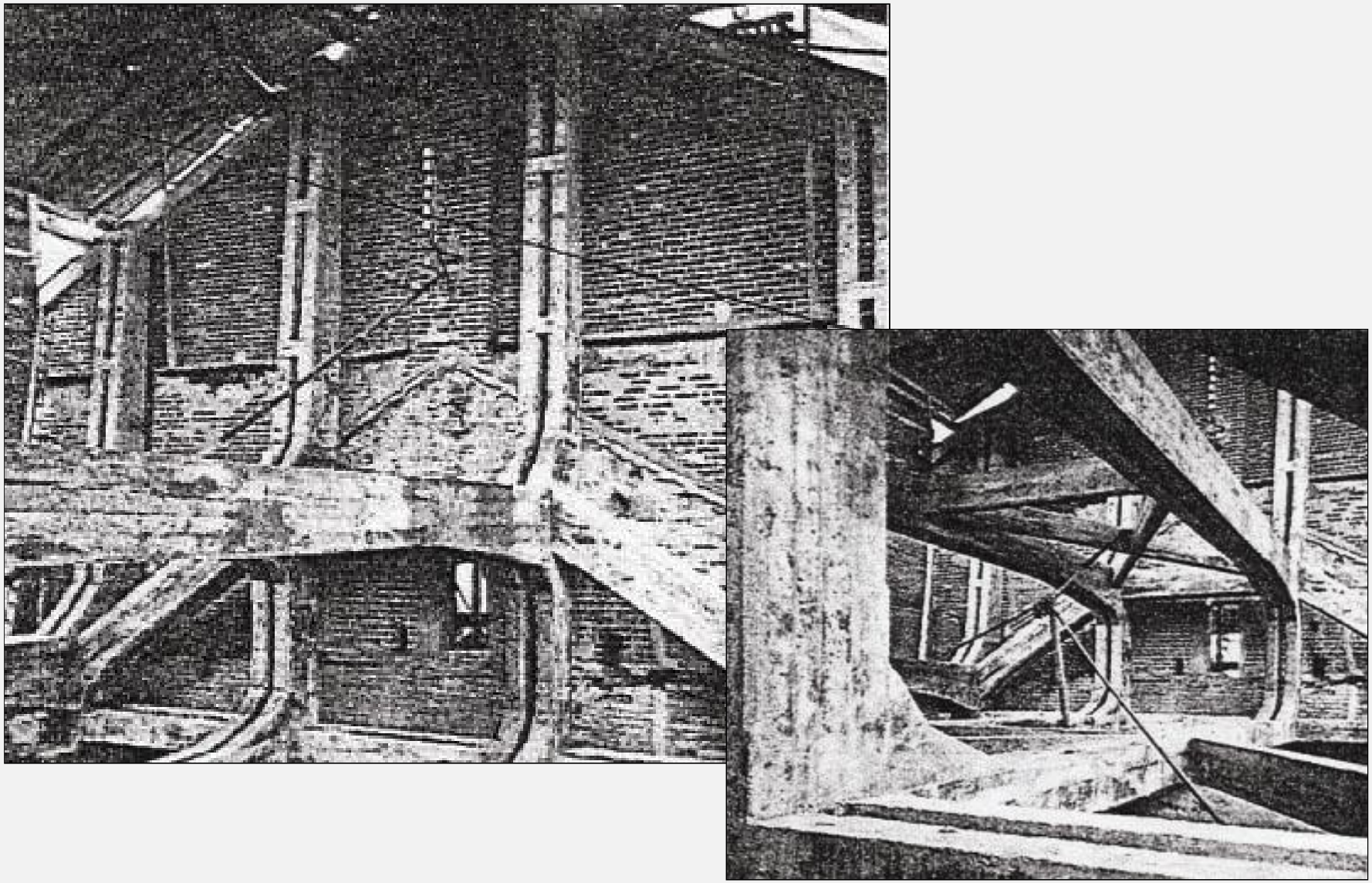
ORDINARY BUILDINGS:

New masonry buildings must be in confined masonry. In repairing existing damaged buildings it is necessary to insert r.c. ring beams and vertical columns inside the masonry walls.

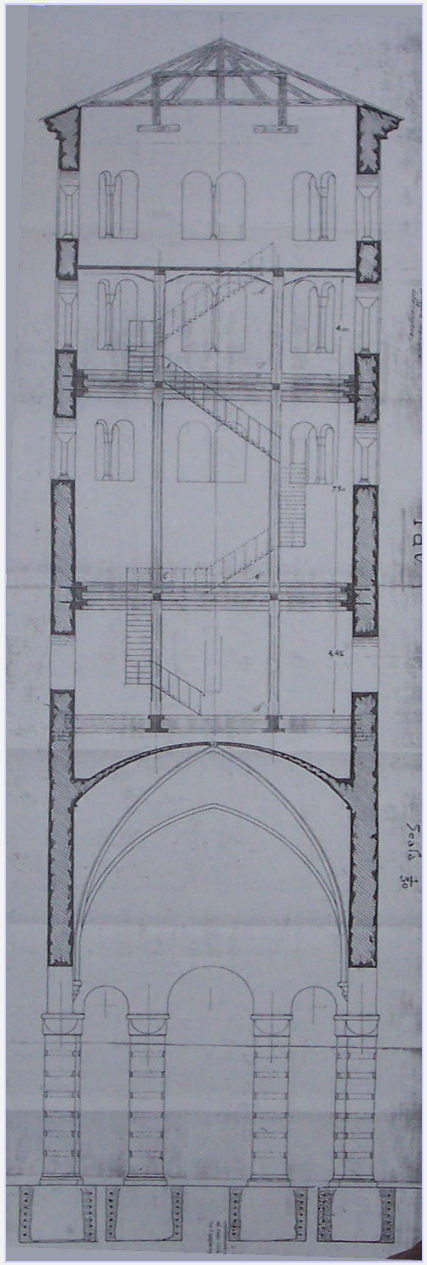
MONUMENTAL STRUCTURES:

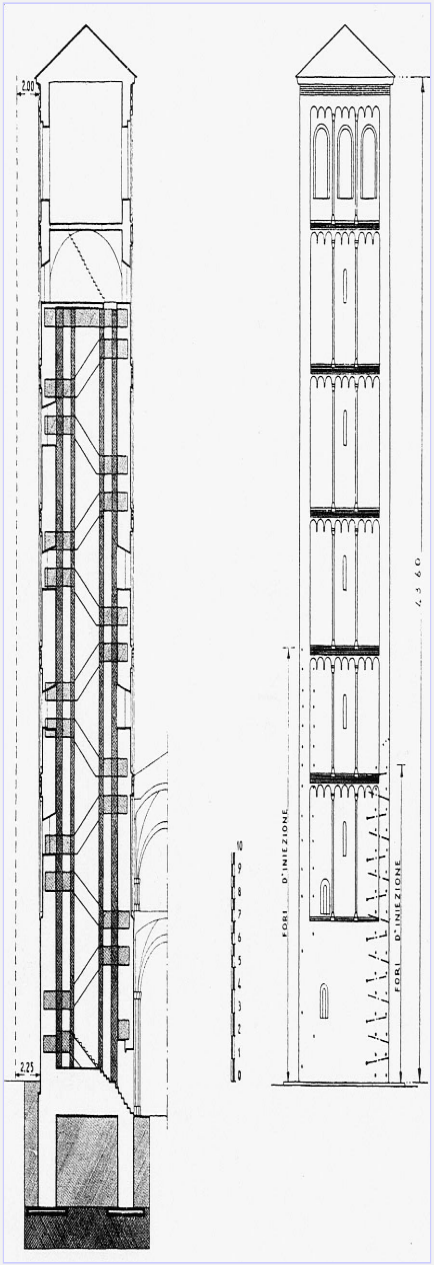
The code states the criteria of "case by case" (nothing is mandatory for monuments). However, in most cases the requirements of safety came first of that of conservation. A lot of interventions with r.c. elements were used in the XX century.

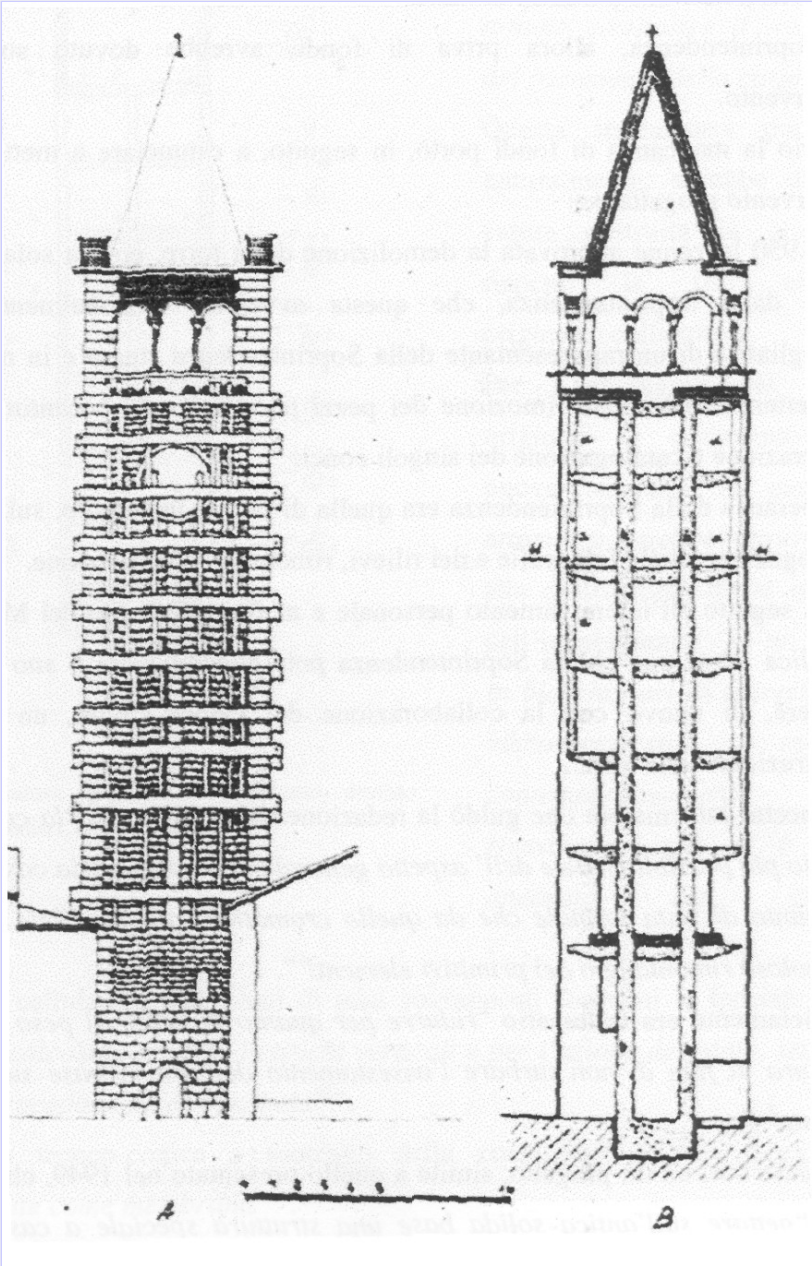
Saint ANDREA CHURCH, VERCELLI – A. GIBERTI,1926.



TOWERS







MOLE ANTONELLIANA, TURIN – A. POZZO, 1930-1936

IRPINIA EARTHQUAKE (1980)

Magnitude 7

- 3000 victims
- 300.000 homeless

NEW SEISMIC CODE (D.M. LL.PP. – July 2, 1981)

Seismic retrofitting: together with the damage repair it is mandatory to upgrade the building, assuring the same safety level as for new buildings.

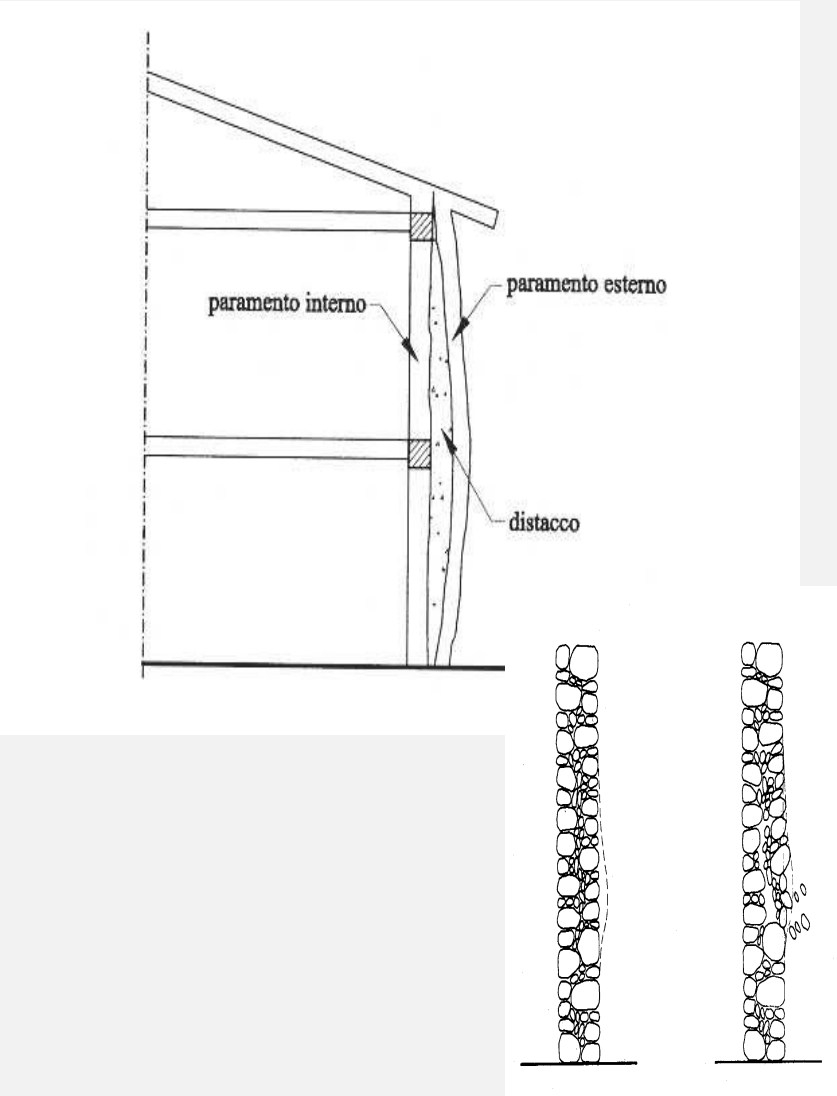
NEED OF MECHANICAL MODELS FOR MASONRY BUILDINGS ✱ **POR METHOD**

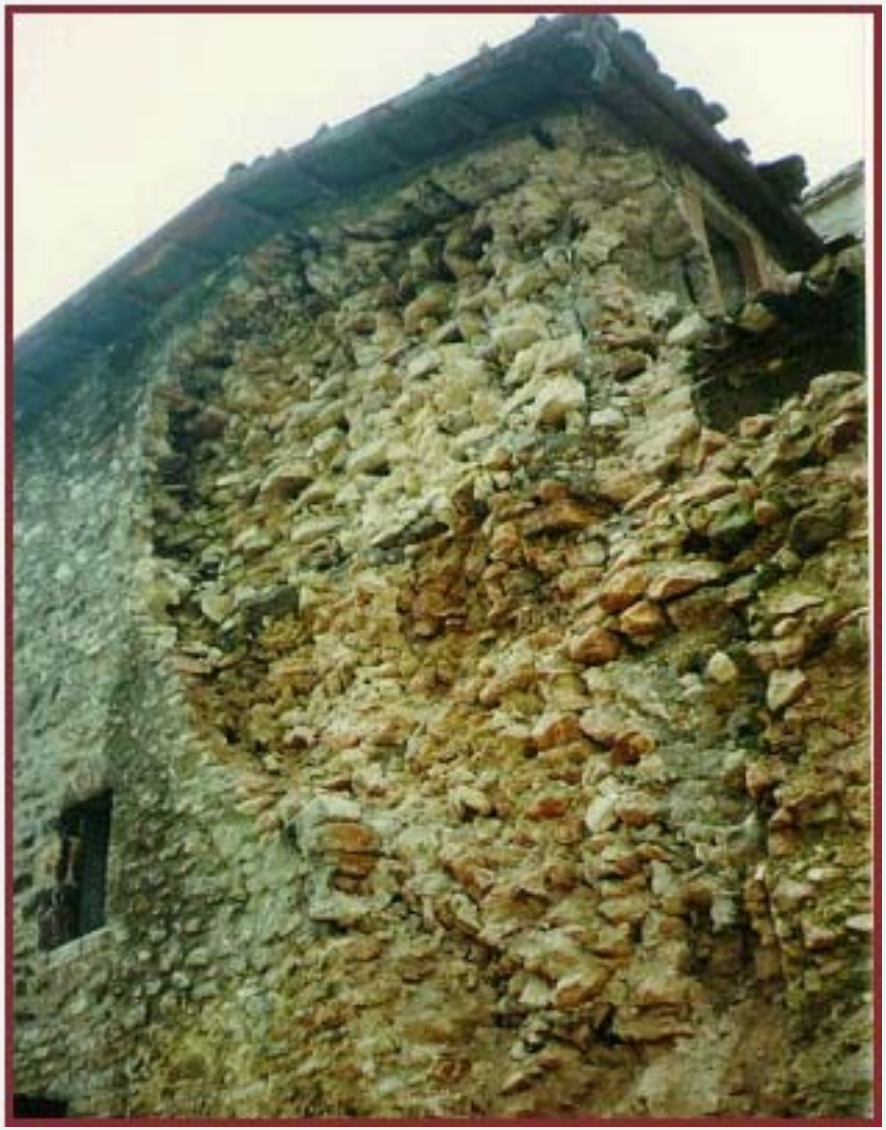
Interventions required for the use of POR:

- r.c. ring beams breaching the masonry wall
- substitution of timber floors with stiff r.c. slabs
- substitution of timber roofs with heavy r.c. slabs

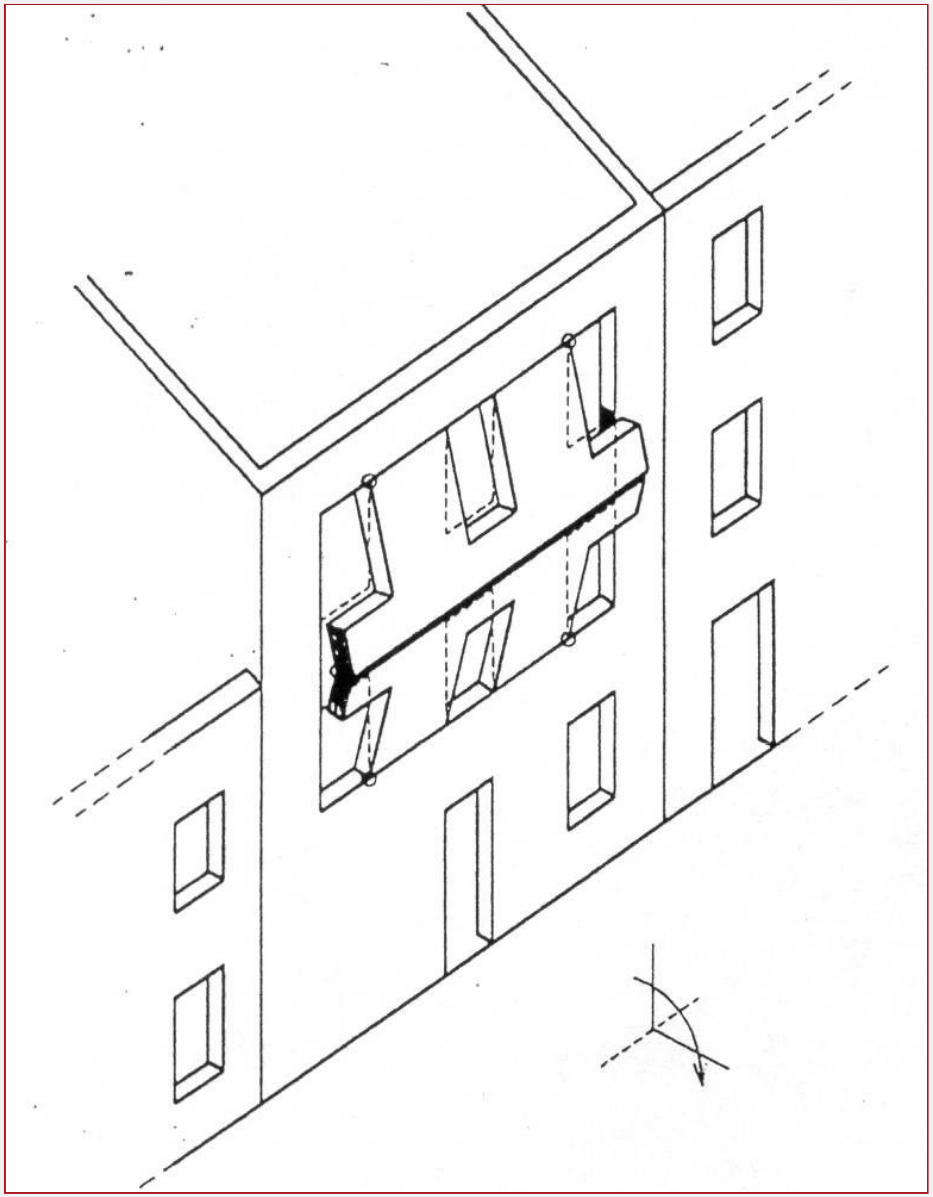
The earthquake proof (Umbria 1997)

Insertion of r.c. ring beams and change of timber floors with r.c. slabs

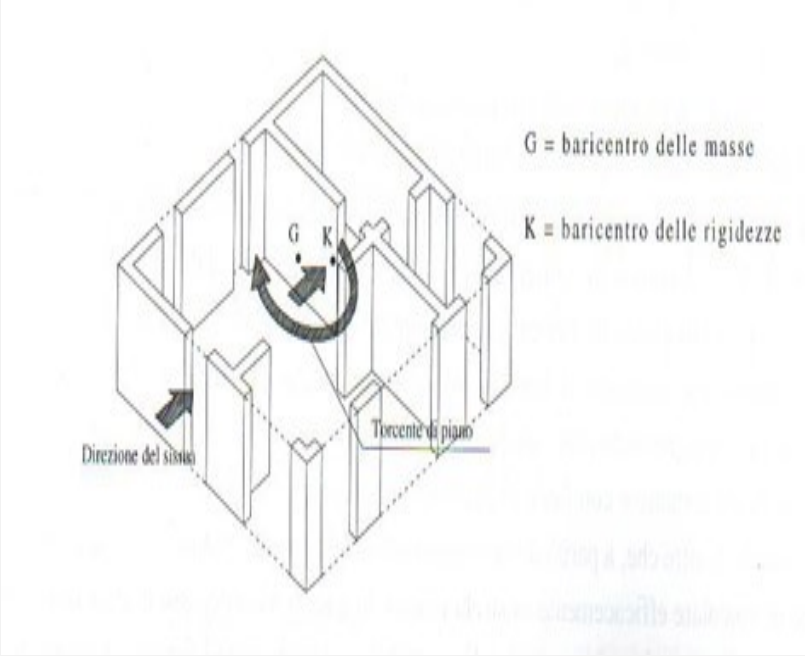




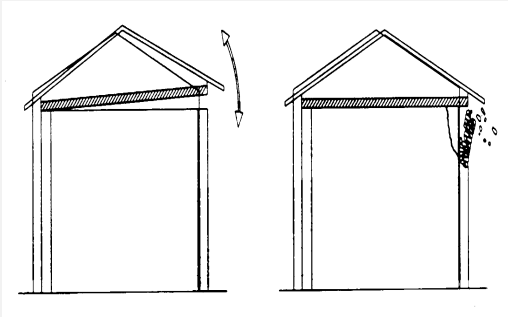
Insertion of r.c. ring beams and change of timber floors with r.c. slabs

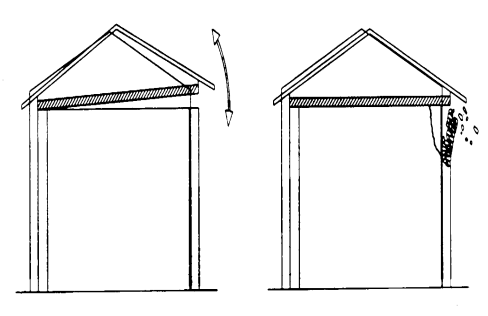


Increase of masses at roof level and torsional effects due to rigid floors



Disgregation and sliding between masonry and r.c. ring beams





The effectiveness of steel tie rods

S. Maria Assunta in Montesanto, Sellano

L'AQUILA EARTHQUAKE
April 6, 2009

Spanish Fortress

SANTA MARIA PAGANICA CHURCH, L'AQUILA

A new approach to seismic strengthening of masonry buildings

Last earthquakes in Italy (L'Aquila 2009, Umbria-Marche 1997) proved the ineffectiveness of invasive and non conservative interventions, based on:

· increasing of stiffness (so reducing the displacement capacity)
· increasing of masses (so increasing the seismic actions)
· modifying the original structural behaviour (so loosing authenticity)

For the reduction of vulnerability in ancient masonry buildings the correct approach should follow this line:

· identify possible failure mechanisms (based on intuition and damage observation, after recent earthquakes, in buildings of the same typology)
· aware use of mechanical models, in order to evaluate the vulnerability and the improvement achieved with different possible intervention strategies
· use again the traditional techniques of intervention, usually effective and compatible with the original behaviour of masonry buildings
· use of innovative materials and techniques, paying attention to lightness, durability and reversibility (FRP, shape memory alloy, dissipative devices,….)

Seismic risk assessment of monumental buildings

MINISTERO PER I BENI E LE ATTIVITÀ CULTURALI
DIREZIONE GENERALE PER I BENI ARCHITETTONICI E PAESAGGISTICI

MiBAC

LA S.V. È INVITATA ALLA GIORNATA DI STUDIO DEDICATA ALLE

Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale

Guidelines for evaluation and mitigation of seismic risk to cultural heritage

1. Aims of the Guidelines
2. Safety and conservation requirements
3. Seismic action
4. The building knowledge (survey and investigations)
5. The seismic analysis of masonry structures
6. Strengthening interventions

volumi pubblicati da
GANGEMI EDITORE

PERPETUATE project (funded by EC in FP7)

PERformance-based aPproach to Earthquake proTection of cUlturAl heriTage in European and mediterranean countries

Main objectives of the project:

- Development of European Guidelines for the evaluation and mitigation of seismic risk to cultural heritage assets.
- Both architectonic assets (historic buildings; macroelements) and artistic assets (frescos, stucco-works, statues, pinnacles, battlements, banisters, balconies …) will be considered. Only masonry structures will be considered.
- Two different scales will be considered:
  a) assessment at the territorial scale including simplified vulnerability and risk analysis and policy issues for seismic risk mitigation
  b) assessment of a single cultural heritage asset and design of interventions

PERPETUATE LOGO

PERPETUATE means "to preserve from extinction"

In the case of cultural heritage assets this means to extend their survival towards **infinity**.

The symbol of infinity is used as a conceptual key for the logo, together with the propagation of seismic waves.

www.perpetuate.eu

PERPETUATE MANIFESTO

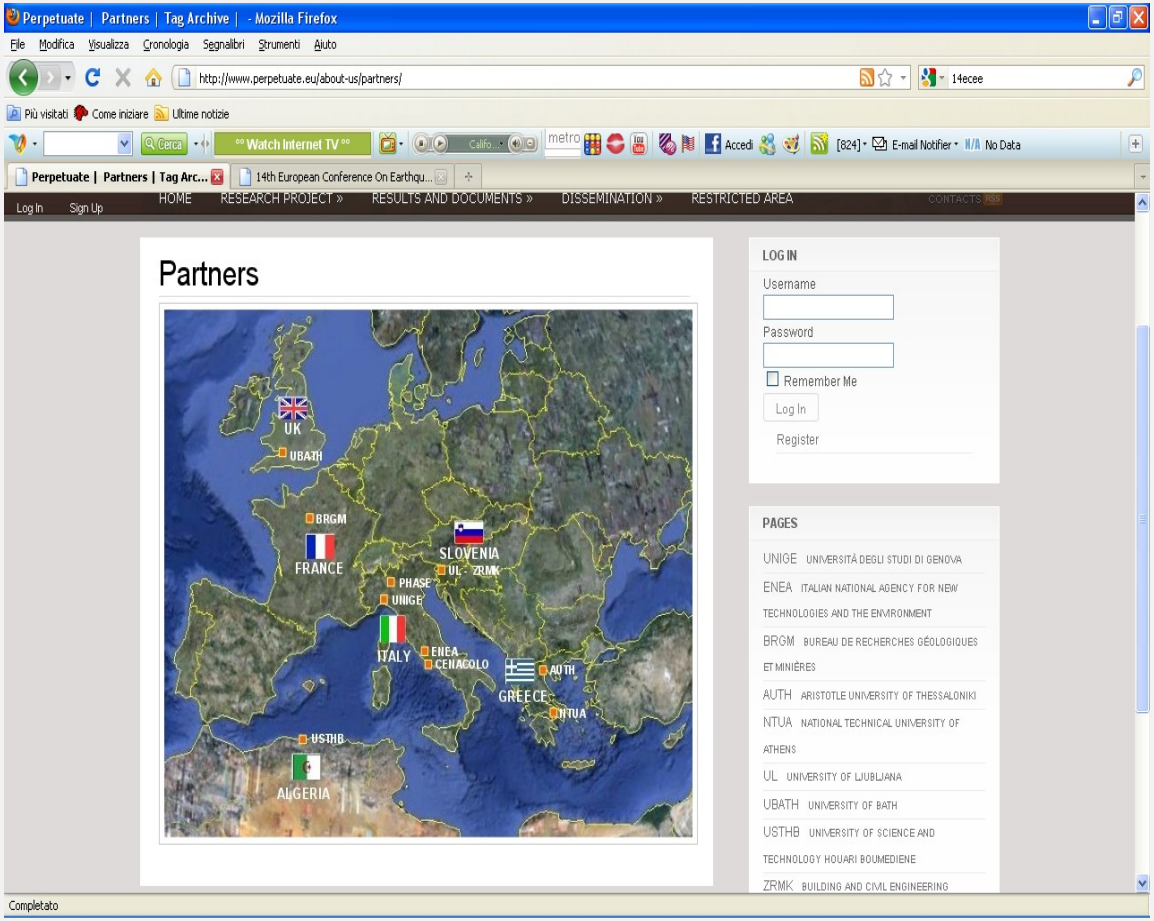
Santa Maria Church in Tempera, L'Aquila (earthquake on April 6, 2009 - h. 3:30)_

www.perpetuate.eu

PARTNERS

The Consortium consists of:

- **6 Universities** (Genoa, Thessaloniki, Athens, Ljubljana, Bath, Algiers)
- **2 Public/Research Institutions** (ENEA, Italy; BRGM, France)
- **3 SMEs** from Slovenia (ZMRK) and Italy (CENACOLO, PHASE).



PROJECT STRUCTURE

WP9
COORDINATION

STEERING COMMITEE

WP1
DEFINITION OF SAFETY LEVELS

WP2
DEFINITION OF THE SEISMIC HAZARD

WP3
FOUNDATION PROBLEMS AND SOIL/STRUCTURE INTERACTIONS

WP6
MODELS FOR THE SEISMIC VULNERABILITY AT TERRITORIAL SCALE

WP4
DIAGNOSTIC TECHNIQUES, MATERIAL PARAMETERS AND STRUCTURAL IDENTIFICATION

WP5
MODELS FOR THE SEISMIC ANALYSIS AND THE DEISGN OF INTERVENTIONS

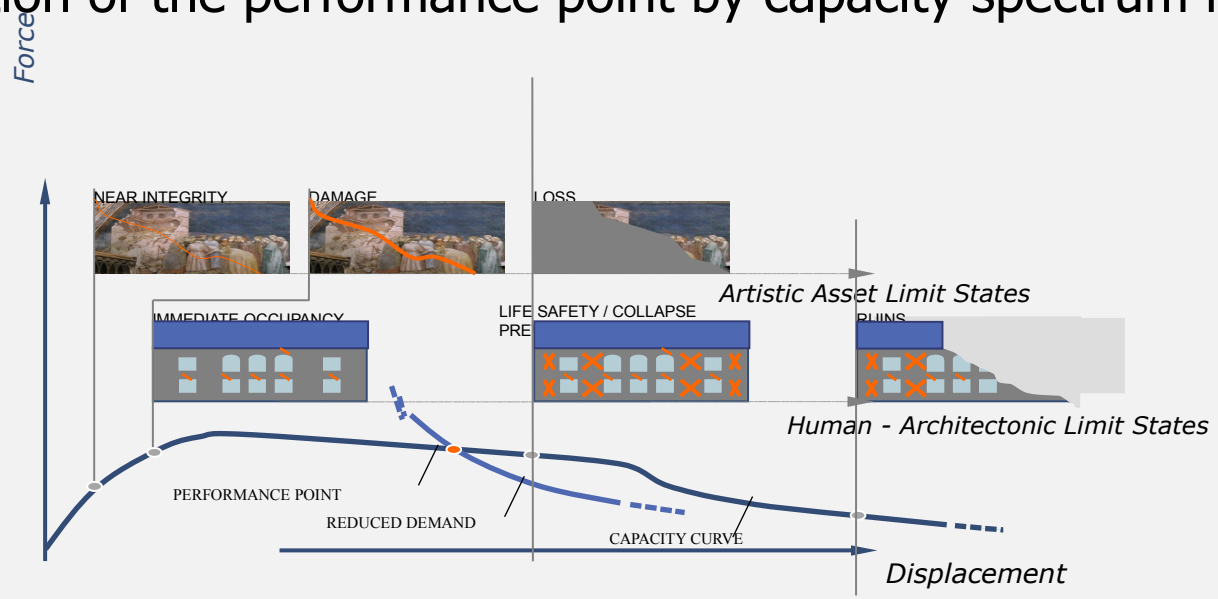
WP7
DEVELOPMENT OF A INTEGRATED METHODOLOGY AND APPLICATION TO CASE STUDIES

WP8
GUIDELINES - DISSEMINATION

PERFORMANCE-BASED ASSESSMENT

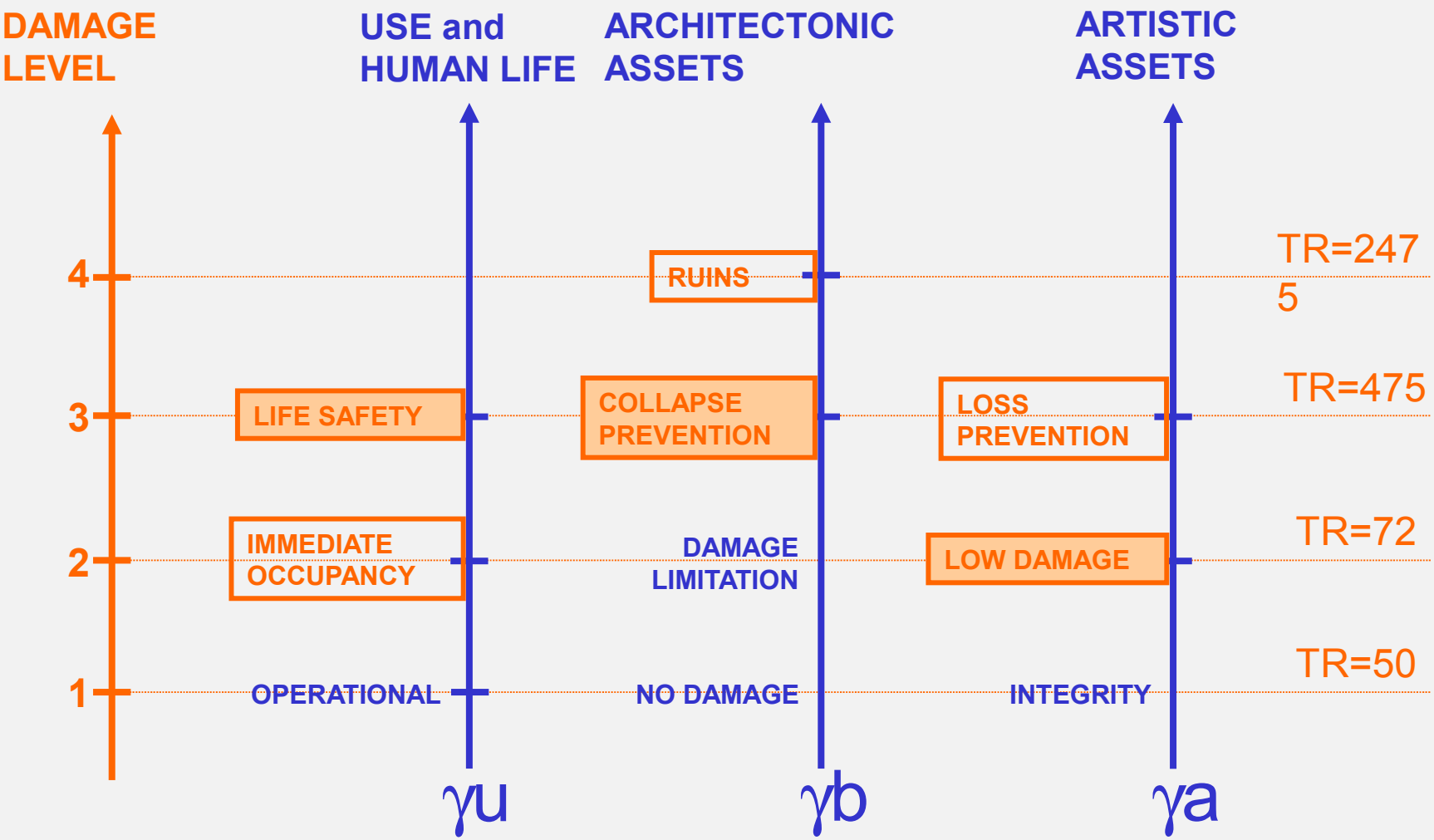
Displacement-based approach for the seismic assessment of architectonic and artistic assets and for the design of strengthening interventions:

1) definiton of the hazard (acceleration-displacement response spectrum)
2) evaluation of the capacity curve by a non linear static analysis
3) indentification of performance limit states
4) evaluation of the performance point by capacity spectrum method



BASIC PERFORMANCE REQUIREMENTS

Main and secondary limit states



BASIC PERFORMANCE REQUIREMENTS

Introduction of coefficients modifying the reference return period

1. USE AND HUMAN LIFE

USE (γu)

FUNCTION OF: BUILDING USE; CROWDING LEVEL.

$\gamma u < 1$ WETHER THE BUILDING IS RARELY USED. IF $\gamma u < 1$, THE ASSESSMENT OF PERFORMANCE LEVEL “IO” IS NOT REQUIRED.

2. ARCHITECTONIC ASSETS

ARCHITECTONIC RELEVANCE (γb)

FUNCTION OF: CULTURAL VALUE OF THE BUILDING ITSELF.

$\gamma b > 1$ WETHER THE BUILDING HAS A PARTICULAR CULTURAL RELEVANCE. $\gamma b > 1$, THE ASSESSMENT OF PERFORMANCE LEVEL “RU” IS REQUIRED

3. ARTISTIC ASSETS

ARTISTIC RELEVANCE (γa)

FUNCTION OF: CULTURAL VALUE OF THE ARTISTIC ASSETS PRESENT IN THE BUILDING.

$\gamma a > 1$ WETHER THE ASSETS HAVE A PARTICULAR CULTURAL RELEVANCE. $\gamma a > 1$, THE ASSESSMENT OF PERFORMANCE LEVEL “LP” IS REQUIRED

CLASSIFICATION OF ARCHITECTONIC ASSETS

It is functional to model main seismic behaviour of buildings

Classes	Description	List of assets
A	This class collects architectonic assets with two main bearing structural elements: **vertical walls** and **horizontal floors**. If they are properly connected, mutual cooperation between the structural elements allows the building to **behave as a box**.	A1 *palaces*, A2 *castles*, A3 *religious houses*, A4 *caravansaries*, A5 *madrasas*
B	This class collects architectonic assets which are characterized by **wide spaces without intermediate floors** and few inner walls. Independent damage mechanisms occurs in the different parts of the building, and it is often possible to recognize **specific structural macroelements** (façade, triumphal arch, apse, dome, transept,…).	B1 *churches*, B2 *mosques*, B3 *temples*, B4 *baptisteries,* B5 *mausoleum*, B6 *hammam* B7 *theatres*
C	This class collects architectonic assets in which the **vertical dimension prevails** on the other ones. Since usually, these buildings are characterized by significant slenderness, their seismic response may be assumed as a **global flexural behavior**.	C1 *towers*, C2 *bell towers*, C3 *minarets*, C4 *lighthouses*, C5 *chimneys*
D	This class collects architectonic assets in which the main structural element is an **arch** or a **vault**. Both single arches or much more complex constructions based on this basic structural element are included.	D1 *triumphal arches*, D2 *aqueducts*, D3 *bridges*, D4 *cloisters*
E	This class collects **massive constructions** in which the wide thickness of walls, if compared to other dimensions, doesn't allow the idealization as plane structural element. **Local failure occurs** as, for example, the detachment of external leaf.	E1 *fortresses*, E2 *defensive city walls*
F	This class collects **single isolated architectonic assets**, which does not delimit an interior space.	F1 *columns*, F2 *trilithes*, F3 *obelisks*, F4 *archaeological ruins*
G	This class refers to **historical centers**, made of ordinary buildings' aggregates, which assume the relevance of cultural heritage asset as whole in the urban context. The seismic response must consider the interaction among adjacent buildings.	

CLASSIFICATION OF ARCHITECTONIC ASSETS

BOX-TYPE STRUCTURES (vertical walls and horizontal floors)

Classes	Description	List of assets
A	This class collects architectonic assets with two main bearing structural elements: **vertical walls** and **horizontal floors**. If they are properly connected, mutual cooperation between the structural elements allows the building **to behave as a box**.	A1 *palaces*, A2 *castles*, A3 *religious houses*, A4 *caravansaries*, A5 *madrasas*

A1 Palaces

A2 Castles

A3 Religious houses

A4 Caravansaries

CLASSIFICATION OF ARCHITECTONIC ASSETS

WIDE HALLS WITHOUT INTERMEDIATE FLOORS (macroelements)

Classes	Description	List of assets
B	This class collects architectonic assets which are characterized by **wide spaces without intermediate floors** and few inner walls. Independent damage mechanisms occurs in the different parts of the building, and it is often possible to recognize **specific structural macroelements** (façade, triumphal arch, apse, dome, transept,…).	B1 *churches*, B2 *mosques*, B3 *temples*, B4 *baptisteries,* B5 *mausoleum*, B6 *hammam* B7 *theatres*

B1 Churches

B2 Mosques

B6 Hammam

CLASSIFICATION OF ARCHITECTONIC ASSETS

SLENDER MASONRY STRUCTURES

Classes	Description	List of assets
C	This class collects architectonic assets in which the **vertical dimension prevails** on the other ones. Since usually, these buildings are characterized by significant slenderness, their seismic response may be assumed as a **global flexural behavior**.	C1 *towers*, C2 *bell towers*, C3 *minarets*, C4 *lighthouses*, C5 *chimneys*

C1 Towers

C2 Bell Towers

C3 Minarets

C4 Lighthouses

CLASSIFICATION OF ARCHITECTONIC ASSETS

DRY BLOCKS SIMPLE STRUCTURES

Classes	Description	List of assets
F	This class collects **single isolated architectonic assets**, which does not delimit an interior space.	F1 *columns*, F2 *trilithes*, F3 *obelisks*, F4 *archaeological ruins*

F1 Columns

F2 Trilithes

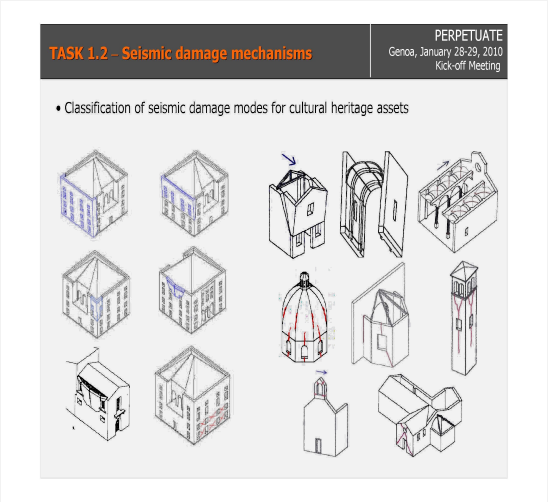
F3 Obelisks

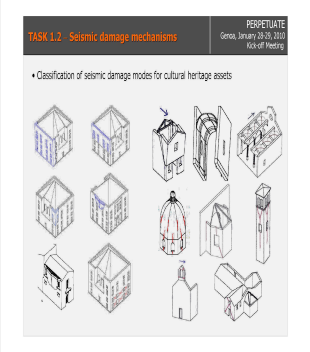
DAMAGE CLASSIFICATION

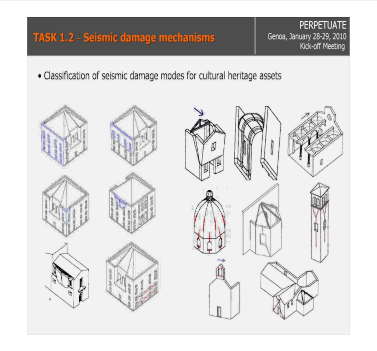
It is possible to identify diff **seis damage modes** for cultural heritage assets, related to iffer sses previously outlined.

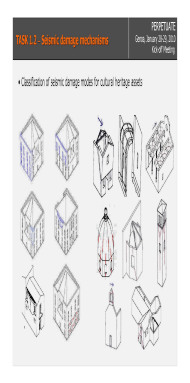
ARCHITECTONIC AND TIC TS CLASSIFICATION

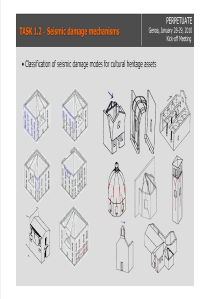
DAMA AS TION











DAMAGE CLASSIFICATION

Correlation between type of building and damage classification

	A	B	C	D	E	F	G
1 – in plane							
2 – out of plane				D2			
3 – flexural/crushing							
4 – arches			C2				
5 – local masonry failure							
6 – blocks							
7 – floors / roofs					E1		
8 – vaults							
9 – domes							

Prevailing behaviour

Possible behaviour

Occasional behaviour

The table above is only qualitative and based most on the presence of macroelements than on frequency of damage.

CLASSIFICATION OF ARTISTIC ASSETS

Class	Description	Sub-class	Examples
P	**Artistic assets which are structural elements themselves**	P1 – carved or shaped vertical structural assets	Caryatid, carved stone columns, walls with carved blocks or shaped bricks, …
		P2 – carved or decorated horizontal structural assets	Carved stone or wooden lintels, decorated wooden beams, …
		P3 – carved structural arched assets	Carved stone arches, vaults and domes, etc.
		P4 – carved or decorated wooden roof	Decorated wooden roof, etc.
Q	**Artistic assets which are strictly connected to structural elements**	Q1 – assets connected to vertical structural elements	Carved stone plates, frescos, mosaics, stuccoes, …
		Q2 – assets connected to the intrados of horizontal and arched structural elements	**Frescos**, **mosaics**, stuccoes, wooden or plaster false ceiling, light thin plaster vaults, …
		Q3 – assets connected to the extrados of horizontal structural elements	Floor with mosaics, decorated tiles, parquets, …
R	**Artistic assets which has their own seismic response**	R1 – assets leant on horizontal structural elements	**Pinnacles**, altars, sculptures, pulpits, …
		R2 – assets jutting out from vertical structural elements	Balconies, shelves, gargoyles, …
		R3 – assets hanging on horizontal structural elements	Lamps, bells, crosses, …

It is functional to model the seismic behaviour

Q - Artistic assets connected to structural elements

· ROSE WINDOWS

· PORTALS

Q -Artistic assets connected to structural elements

· San Bernardino, L'Aquila

Q - Artistic assets connected to structural elements

· LATHWORK VAULTS

Fig. 15. Volta in camorcanna in corrispondenza di due crolli. a) arellato intrecciato, b) malta al di sopra delle canne.

· FRESCOES

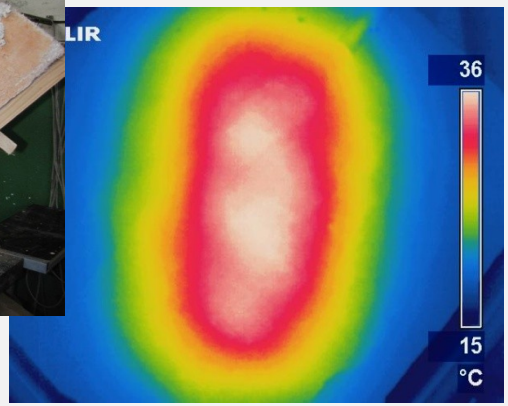
R - Artistic assets with their own seismic response

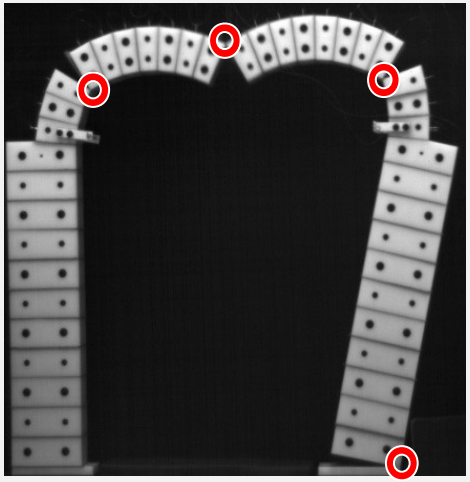
· PINNACLES, STATUES

· CORBELS, GARGOYLES

EXPERIMENTAL TESTS FOR THE LIMIT STATES

- UL – UNIGE: Static test on masonry panels (raking tests, diagonal compression tests)
- CENACOLO: Evaluation of damage limit states for artistic assets (frescoes, mosaics), applied to the masonry panels
- ENEA – UNIGE: Static and shaking table tests on an arch-pillars system
- ENEA: Shaking table test on Obelisco Lateranense (Rome)



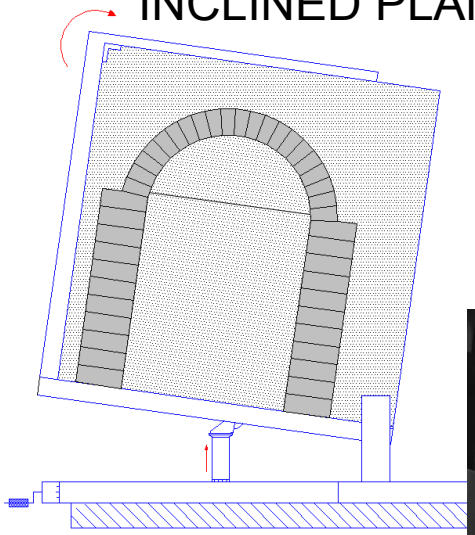


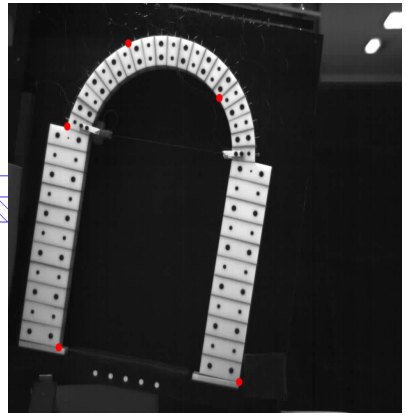
LIMIT STATES FOR AN ARCH-PIER SYSTEM

TESTS ON AN ARCH-PIERS SYSTEM REINFORCED WITH TIE-RODS

STATIC TESTS
Laboratory of University of Genoa

INCLINED PLANE TESTS





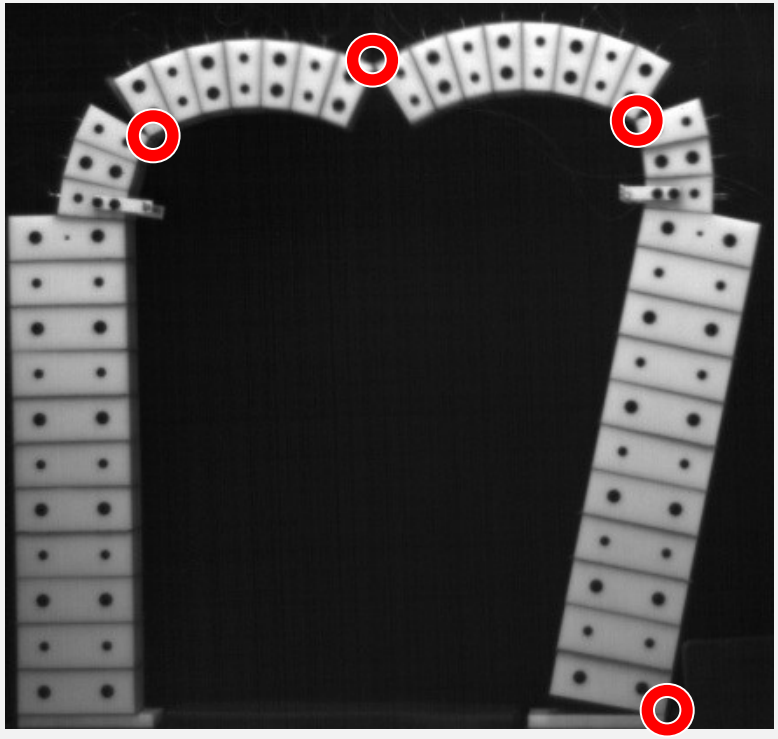
DYNAMIC TESTS
Laboratory of ENEA

SHAKING TABLE TESTS

ARCH-PIER SYSTEM – STATIC TESTS

TESTS ON AN ARCH-PIERS SYSTEM REINFORCED WITH TIE-RODS

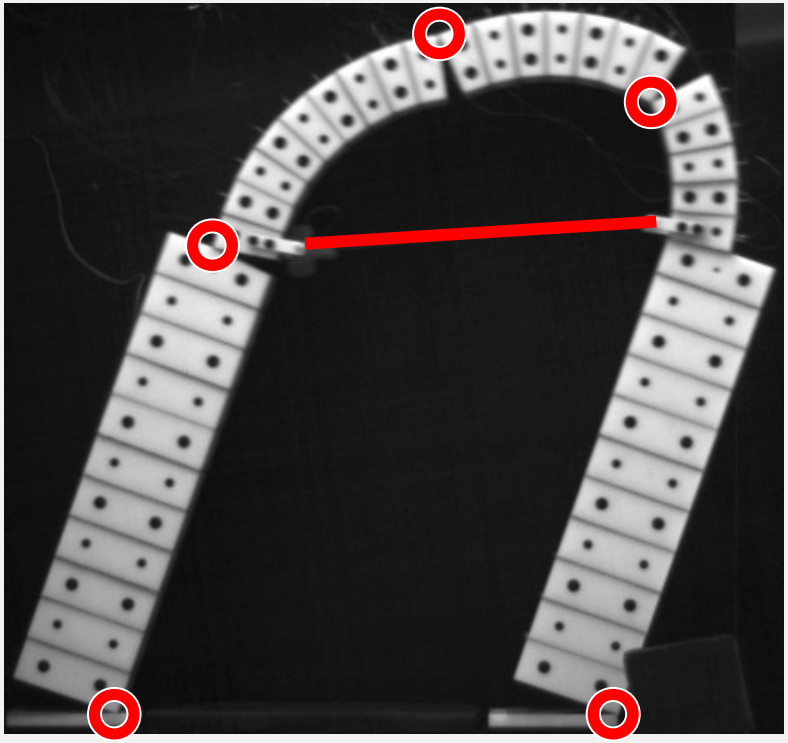
STATIC TESTS



WITHOUT TIE-ROD

4 hinges mechanism

$\alpha = 0.1$ (horizontal multiplier)



WITH TIE-ROD

5 hinges mechanism

$\alpha = 0.19$ (horizontal multiplier)

ARCH-PIER SYSTEM – SHAKING TABLE TESTS

WP2 – DEFINITION OF THE SEISMIC HAZARD

Objectives

- Providing reliable tools to characterize the seismic input for the specific case of cultural heritage assets.
  - *Probabilistic and deterministic methods*
  - *Local soil and site effects including topography, soil non-linearity, basin edge effects, "source" and "path" effects.*
- Definition of proper intensity measures of the seismic action for cultural heritage buildings.
- Definition of Demand Spectra for different soil categories.

AUTH - University of Thessaloniki – K. Pitilakis
NTUA - University of Athens – G. Gazetas
BRGM France – H. Modaressi

Characterization of the seismic hazard for historical buildings

- **Accounting for site effects**
  - Accounting for valley and basin effects
  - Accounting for steep topography
  - Accounting for specific site conditions (e.g. very soft soil)

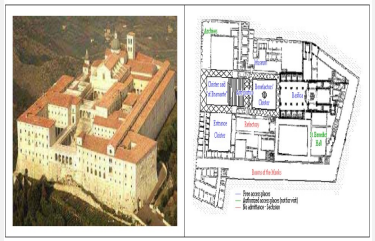


Figure 4.32. Class A3 - The abbey of Monteccasino, Italy.

Figure 4.40. Class C1 – Asinelli Towers in Bologna (Italy).

- **Accounting for long periods**
  - C (Towers), B (out of plane mechanisms), F (blocky structures)
- **When elastic response spectrum is not an adequate descriptor of hazard**
  - F and G (which include elements subject to rocking or sliding, i.e. rigid block r base; rigid block sliding on a horizontal or sloping rigid base)
  - Sensitive to forward-directivity and fling-step affected motions, which contain severe acceleration pulses and/or velocity s
- **Accounting for the vertical component**
- **Accounti nt displacement**

Figure 4.19. Class C - Damage to masonry elements subjected to combined axial and bending loads: towers.

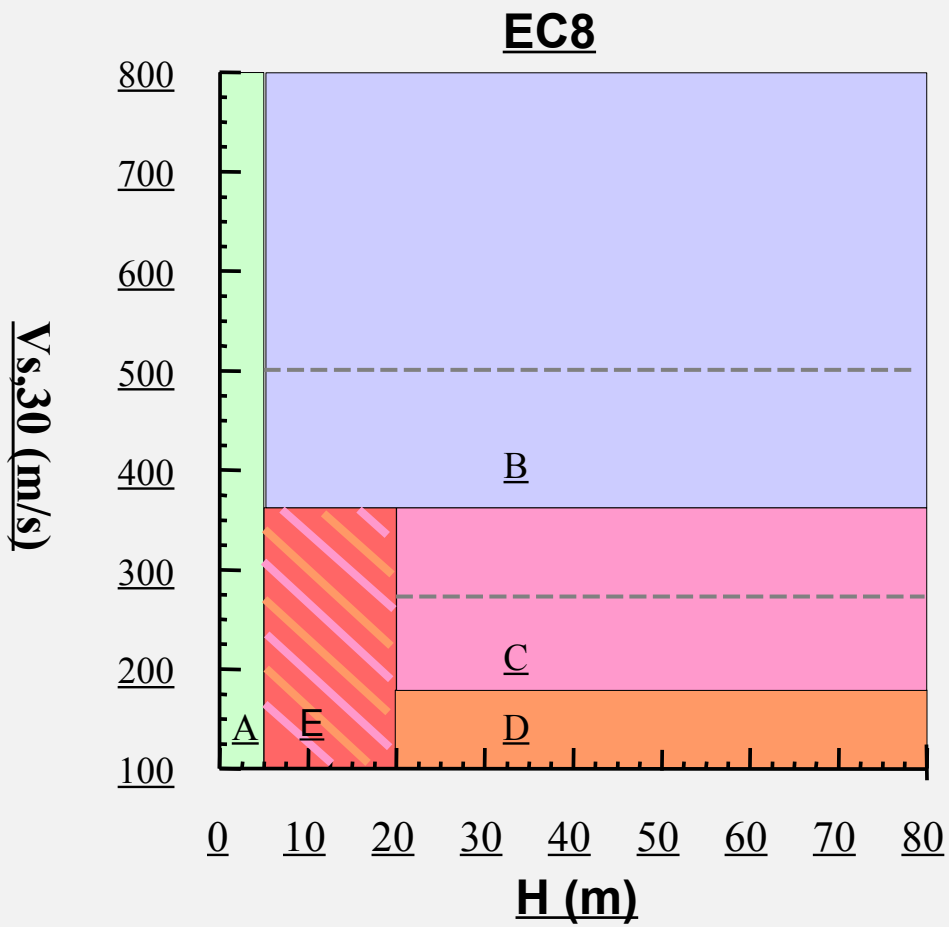
Response of isolated columns composed by large stone blocks: sliding occurred among adjacent blocks.

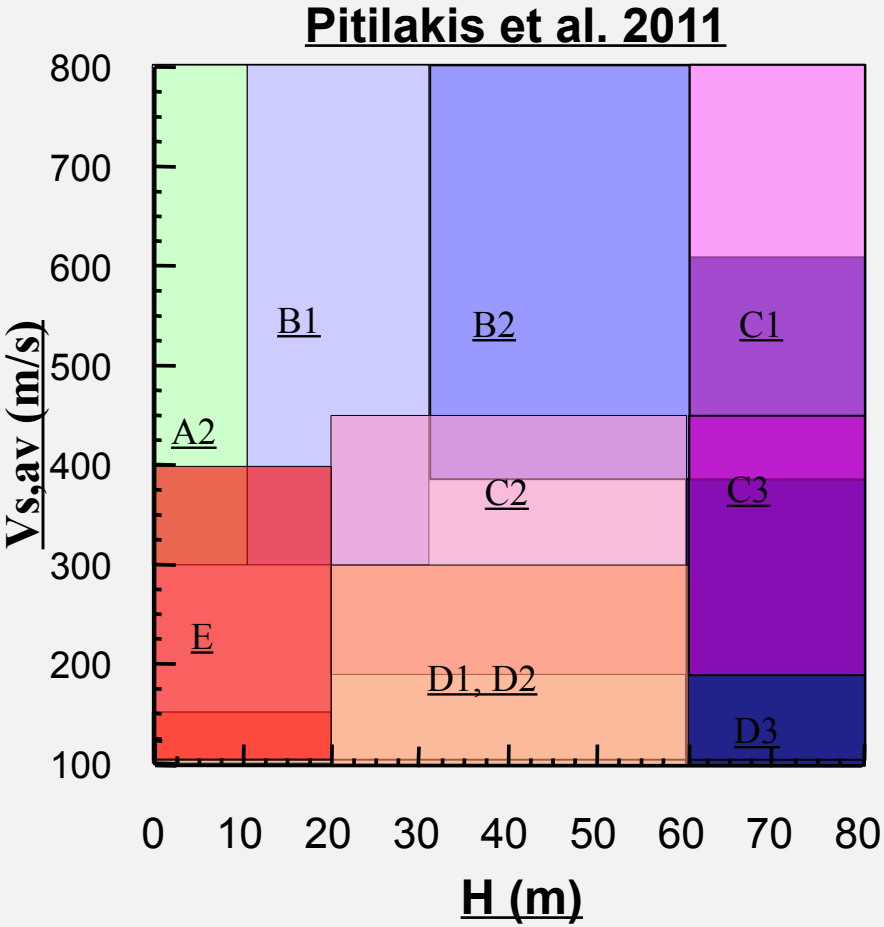
Response of isolated columns composed by large stone blocks: rocking with block failure.

Figure 4.26. Class F – Rocking of single or multiple blocks: case of columns made by large stone blocks.

Figure 4.45. Classes E1/E2 – On the left, Kluze Fortress (Slovenia); on the right, defensive city walls of Thessaloniki (Greece).

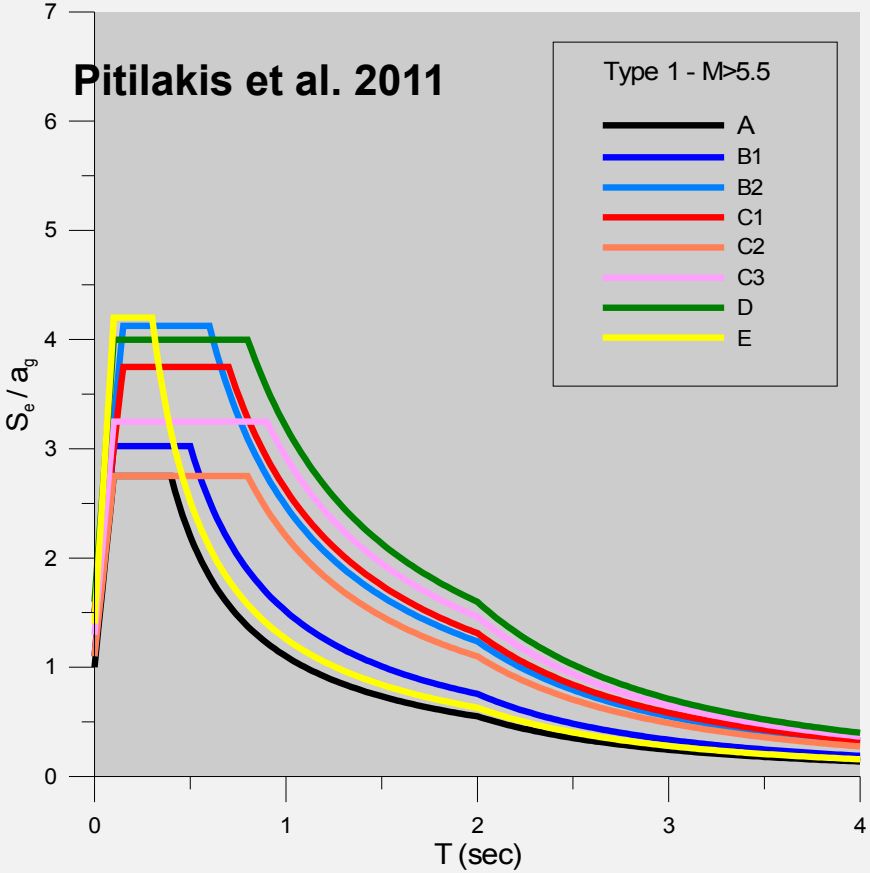
New soil & site classification scheme

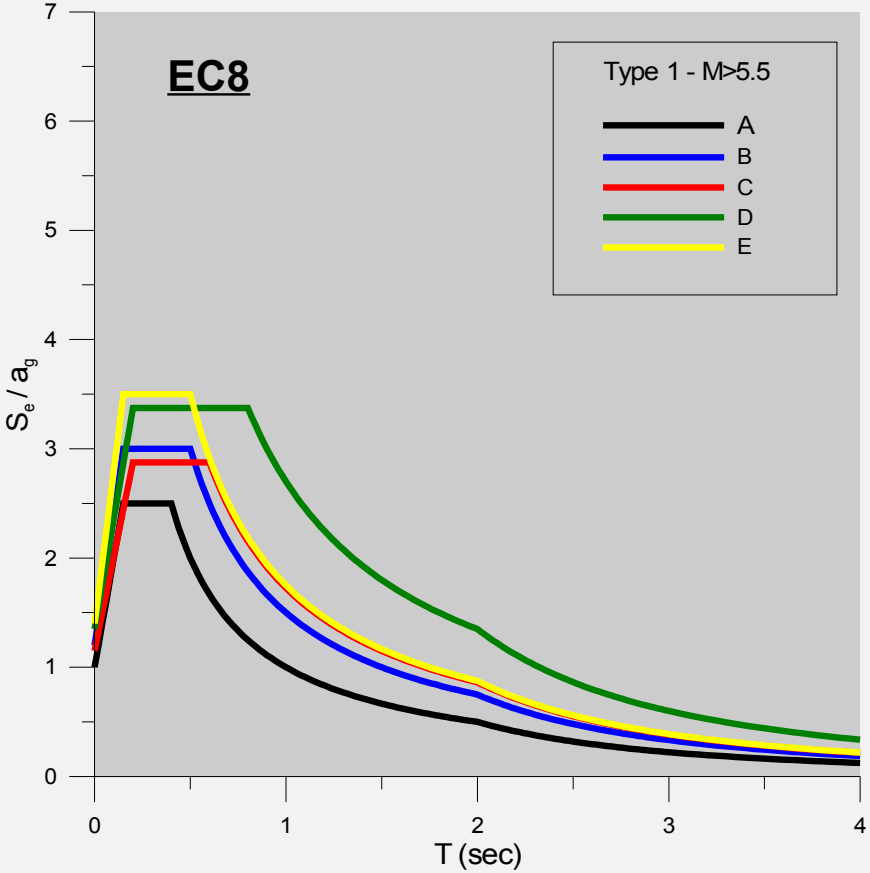




New soil & site classification scheme

Type 1 – Ms>5.5 acceleration spectra

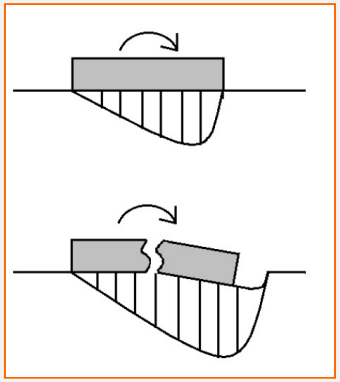


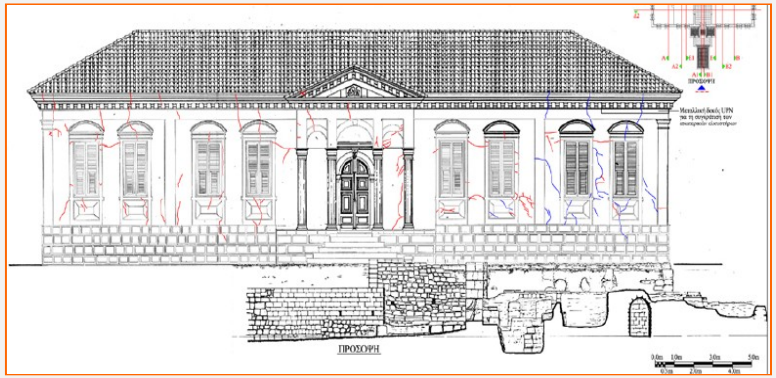


WP3 – Foundation problems, soil/structure interactions

Objectives

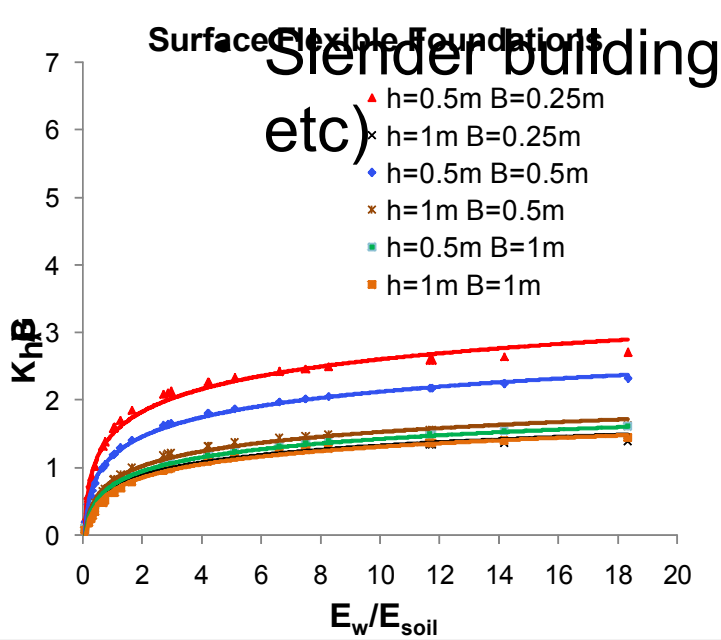
- Analysis of the SFI effects and wave propagation
- Vulnerability assessment of masonry foundations for permanent ground displacements
- Development of a simplified model for the evaluation of impedance functions for flexible foundations
- Field and laboratory physical validation tests

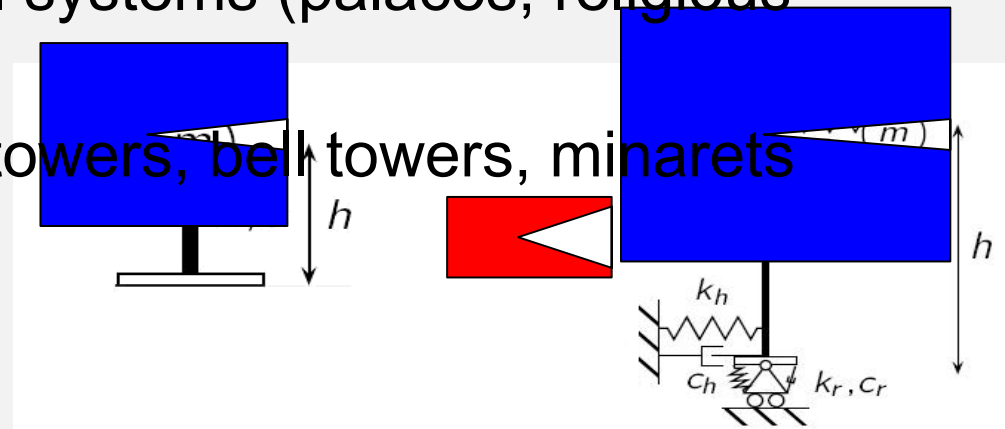




NTUA - University of Athens – G. Gazetas
AUTH - University of Thessaloniki – K. Pitilakis

- **Intense SFSI effects can occur in:**
  - Significant mass (palaces, castles, mosques etc)
  - Complex structural systems (palaces, religious houses etc)
  - Slender buildings (towers, bell towers, minarets etc)



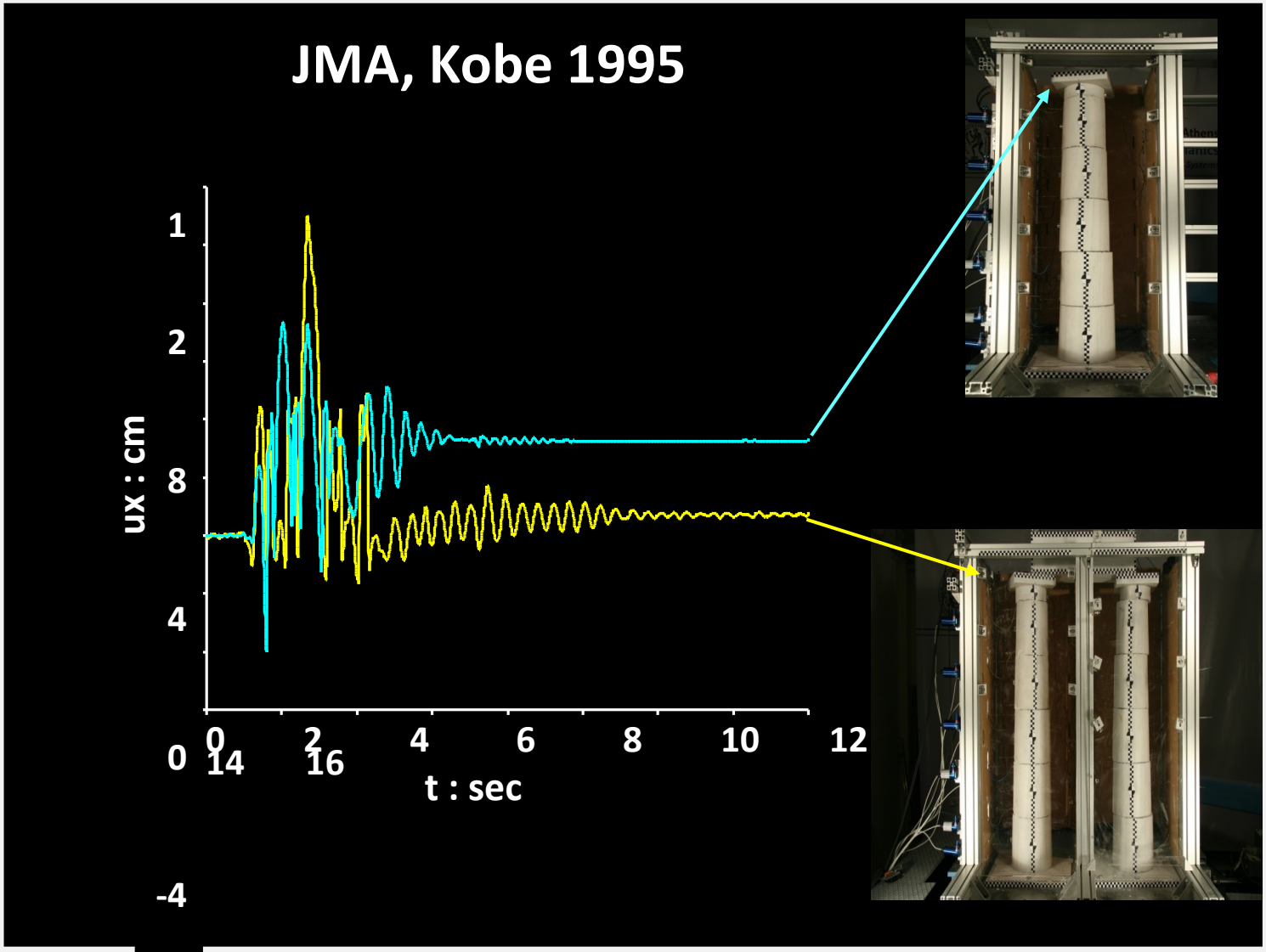


$$K_f = \left\{ a' \left(\frac{E_w}{E_s} \right)^2 + b' \left(\frac{E_w}{E_s} \right) + c \right\} GB$$

Embedded Foundations									
h/2B	Horizontal stiffness (kN/m/m) $K_h = \left\{ a \times \ln\left(\frac{E_w}{E_s}\right) + b \right\} GB$		Vertical stiffness (kN/m/m) $K_v = \left\{ a \times \ln\left(\frac{E_w}{E_s}\right) + b \right\} GB$		Rocking stiffness (kNm/m/m) $K_r = \left\{ a \times \ln\left(\frac{E_w}{E_s}\right) + b \right\} GB$		$K_r = \left\{ a \times \left(\frac{E_w}{E_s}\right)^2 + b \times \left(\frac{E_w}{E_s}\right) + c \right\} GB$		
	a	b	a	b	a	b	a	b	c
0.05	0.074	0.16	0.054	0.14	-	-	-0.0001	0.030	0.016
0.1	0.104	0.195	0.074	0.163	-	-	-0.002	0.122	0.057
0.2	0.129	0.227	0.102	0.195	-	-	-0.01	0.494	0.285
0.25	0.407	0.906	0.379	0.87	-	-	-0.003	0.153	0.089
0.5	0.644	1.442	0.608	1.367	-	-	-0.012	0.396	0.33
1	0.824	2.175	0.791	1.999	1.148	2.773	-	-	-
2	1.150	2.838	1.025	2.651	1.752	5.994	-	-	-
4	1.224	3.455	1.086	3.181	3.078	15.69	-	-	-

WP3 – Foundation problems, soil/structure interactions

Shaking table tests on blocky structures with different foundation systems



WP4 – Diagnostic Techniques and Material Parameters

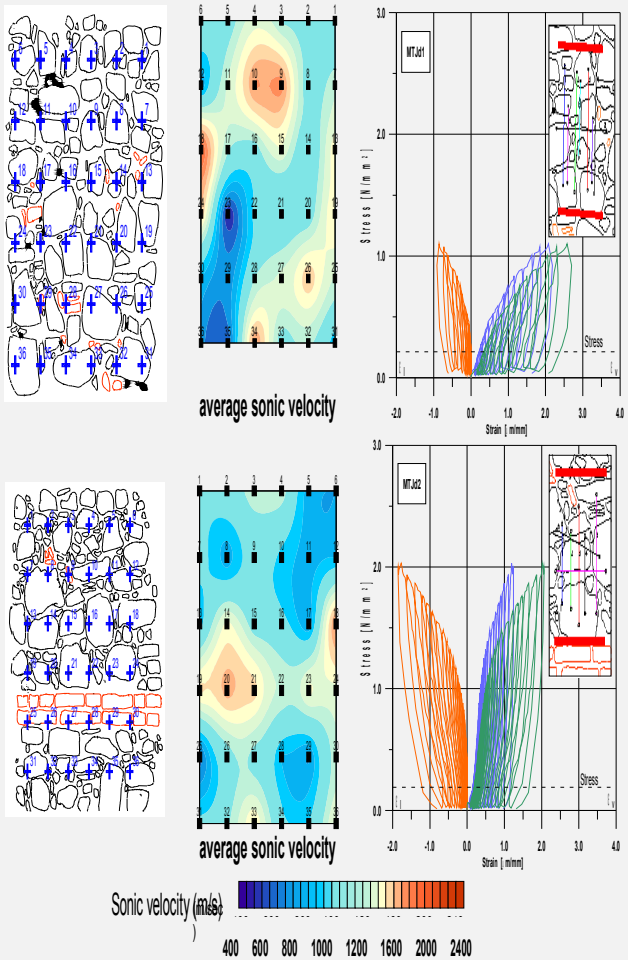


Fig. 12 – Results of sonic and flat-jack tests carried out in Taggia.

UL - University of Ljubljiana – V. Bosjlikov

WP5 – Mechanical models for assessment and design

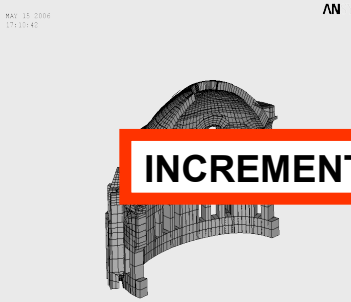
GLOBAL MODELS

IN-PLANE MECHANISMS

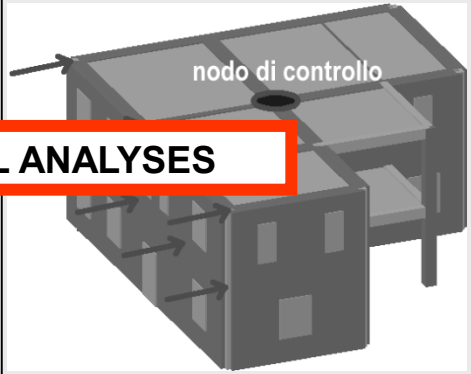
LOCAL MODELS

OUT-OF-PLANE MECHANISMS

A) FINITE ELEMENTS

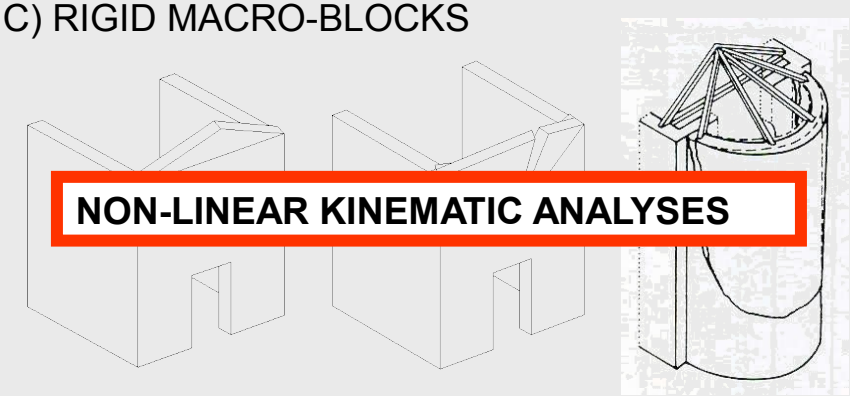


B) STRUCT. ELEMENTS



INCREMENTAL ANALYSES

C) RIGID MACRO-BLOCKS



NON-LINEAR KINEMATIC ANALYSES

WP5 – Mechanical models for assessment and design

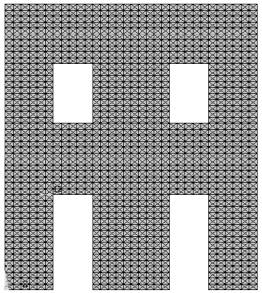
Material scale

Element scale

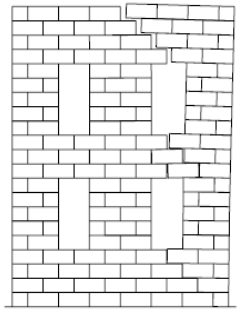
Continuous models

Discrete models

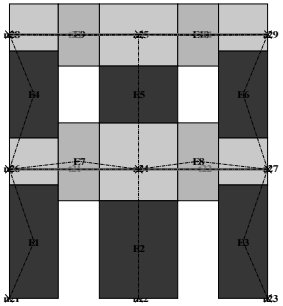
Continuum finite element model with non-linear constitutive law



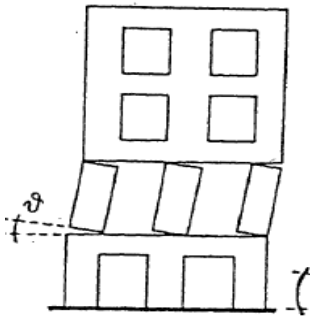
Discrete interface model



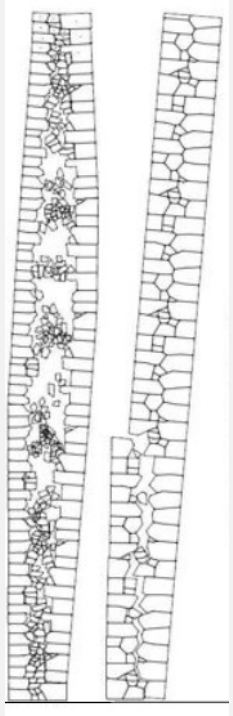
Structural element model (piers and spandrels)

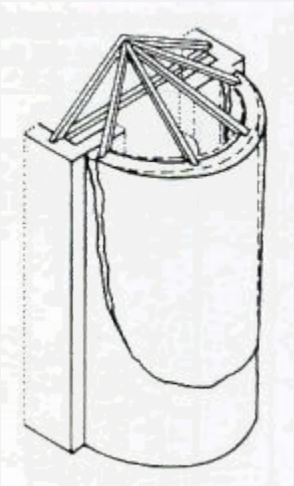


Discrete Macro-block model



b)





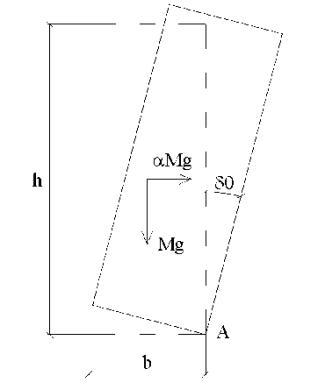
CORRELATION BETWEEN BUILDING CLASSES AND MODELS

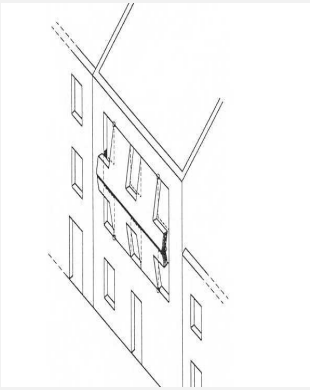
Architectonic asset class		Models			
		CCLM	SEM	DIM	MBM
A	Assets subjected to prevailing in-plane damage		Global		Local
B	Assets subjected to prevailing out-of-plane damage				
C	Assets characterized by monodimensional masonry elements				
D	Arched structures subject to in-plane damage				
E	Massive structures in which local failure of masonry prevails				
F	Blocky structures subjected to overturning				
G	Built systems subjected to complex damage		Global		Local

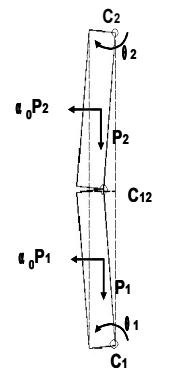
WP5 – Mechanical models for assessment and design

· TASK 5.1 – Modelling of local mechanisms of buildings

OUT-OF-PLANE MECHANISMS
(1° failure mode)







- **LIMIT ANALYSIS – KINEMATIC APPROACH**
- **PUSH-OVER CURVE THROUGH NON LINEAR KINEMATIC ANALYSIS**

$\lambda = amax / g$

WP5 – Mechanical models for assessment and design

$$\theta_2 = \theta_1 \frac{(y_B - y_A)(x_C - x_D) + (y_C - y_D)(x_A - x_B)}{(y_B - y_C)(x_C - x_D) + (y_C - y_D)(x_C - x_B)}$$

$$\theta_3 = \theta_1 \frac{(y_B - y_A)(x_C - x_B) + (y_C - y_B)(x_A - x_B)}{(y_D - y_C)(x_B - x_C) + (y_B - y_C)(x_C - x_D)}$$

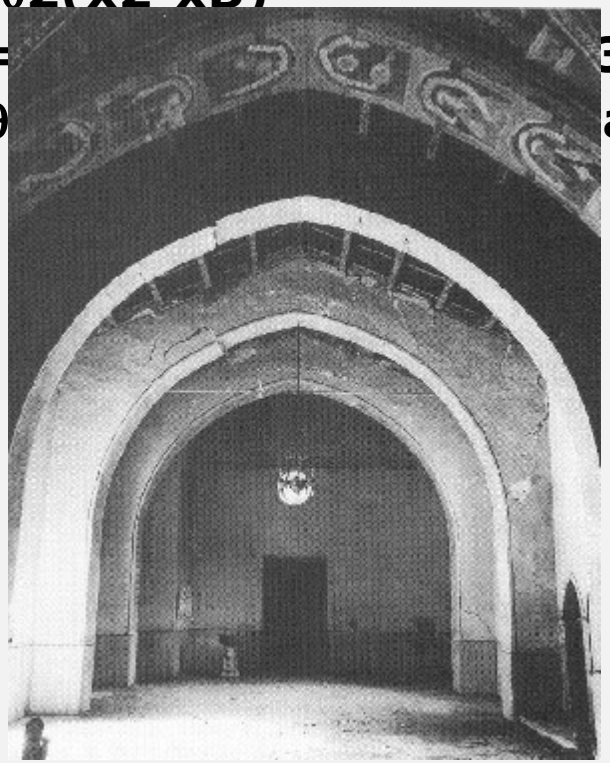
$$\sum_{i=1}^{3} P_i \Delta y_i - \alpha \sum_{i=1}^{3} P_i \Delta x_i = T \Delta l$$

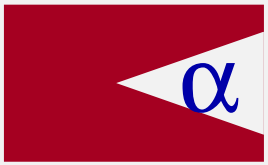
$\Delta x1 = \theta 1(yA-y1)$ $\Delta y1 = \theta 1(x1-xA)$

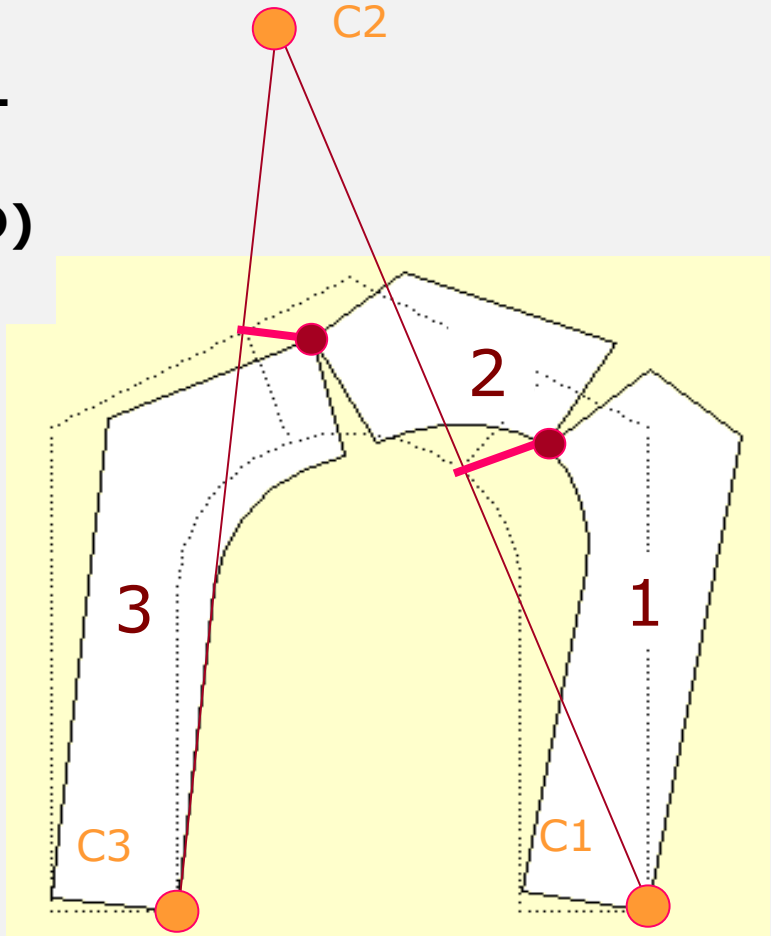
$\Delta x2=\theta 1(yA-yB)+\theta 2(yB-y2)$ $\Delta y2=\theta 1(xB-xA)+\theta 2(x2-xB)$

$\Delta x3 =$ [illegible] $3 = \theta 3(x3-xD)$

$\Delta l = \theta$ [illegible] atena-yA)

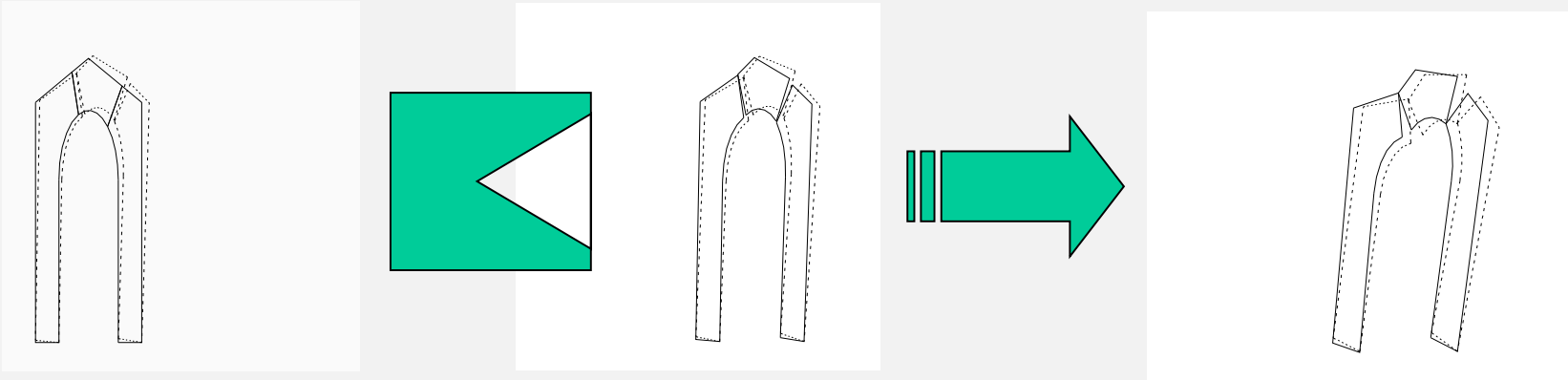




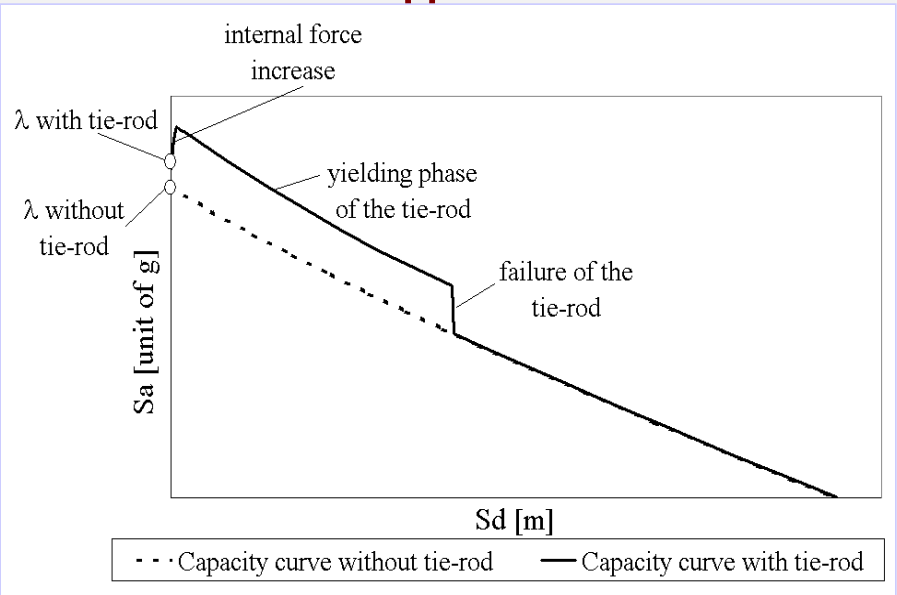


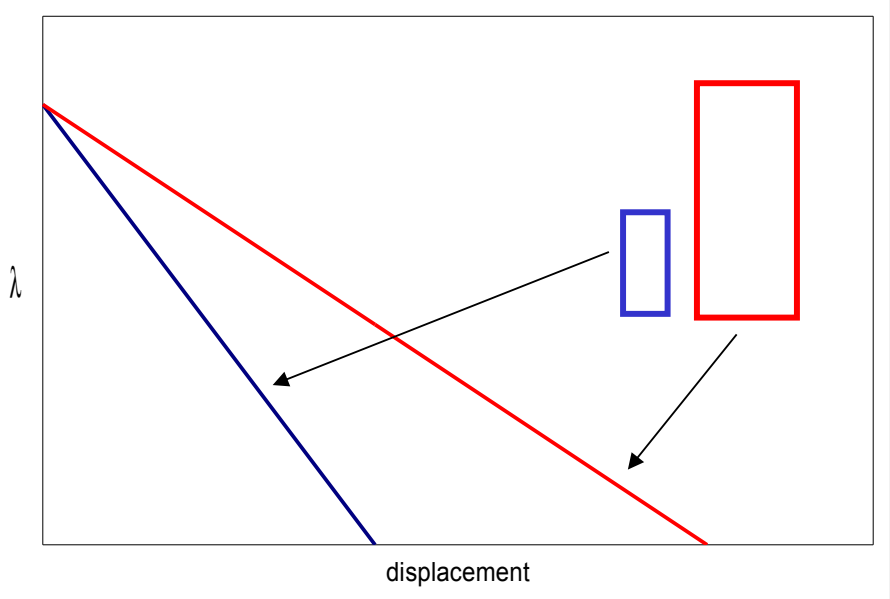
WP5 – Mechanical models for assessment and design

Pushover curve by equilibrium limit analysis



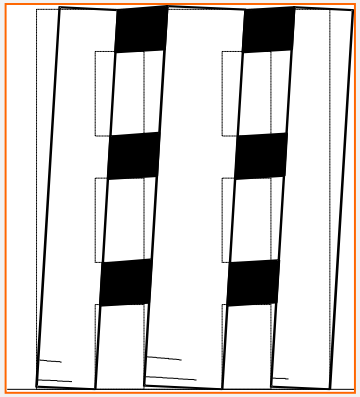
Step 0 → α0 Step 1 → α1 Step i → αi

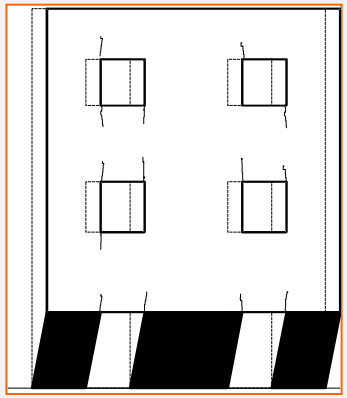




WP5 – Mechanical models for assessment and design

· TASK 5.2 – Modelling of global response of buildings

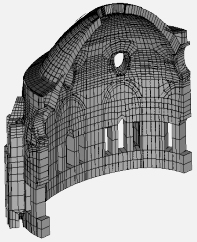


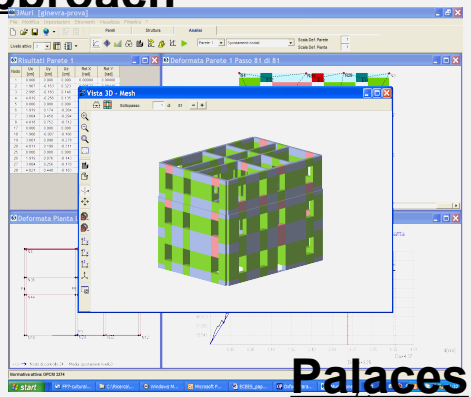


IN-PLANE MECHANISMS
(2° failure mode)

Finite element approach

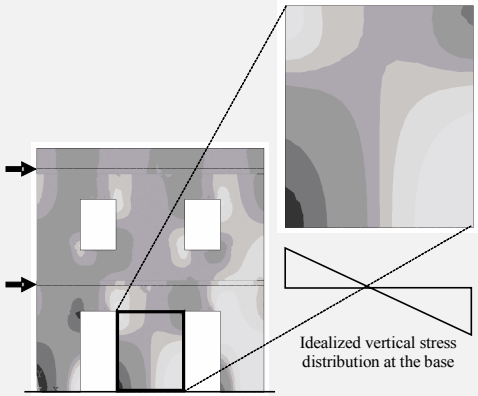
Structural element approach

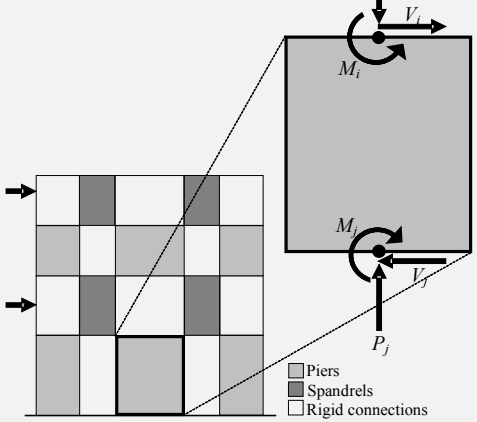




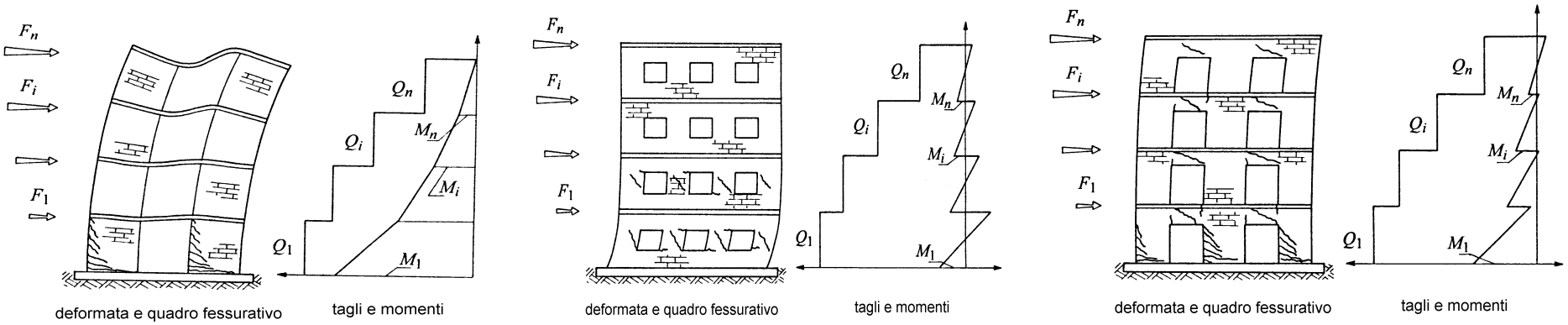
Churches

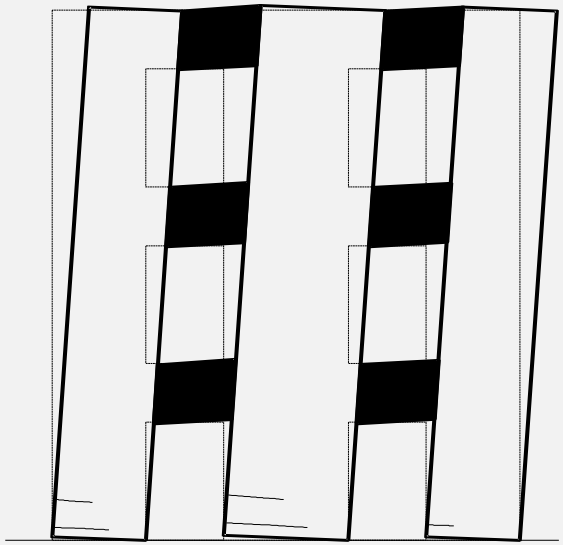
Palaces



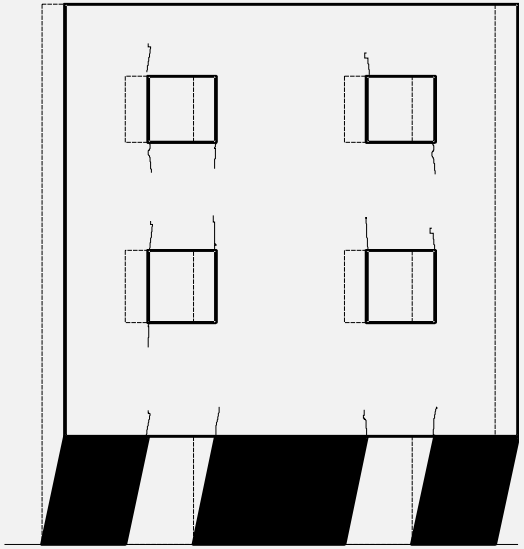


NON LINEAR PUSHOVER ANALYSIS



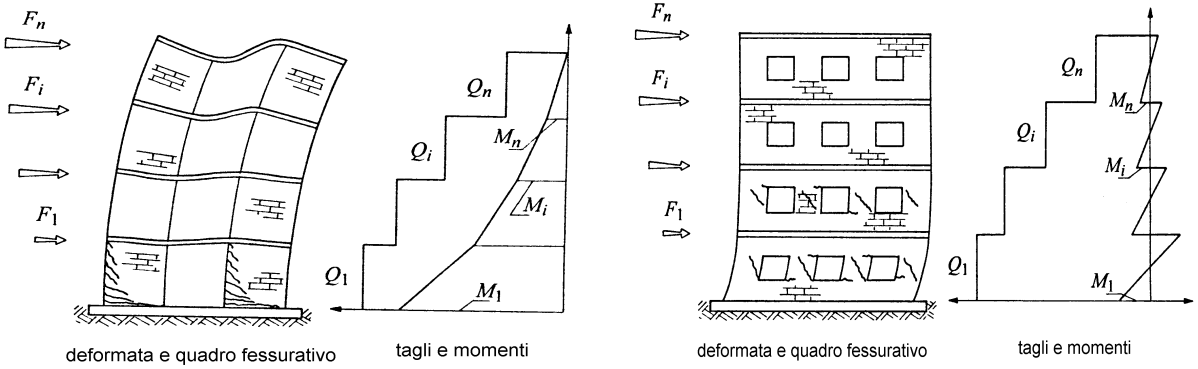


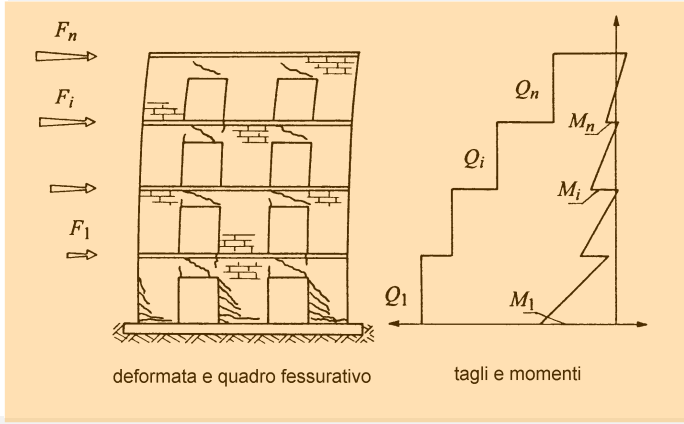
WEAK SPANDRELS
STRONG PIERS



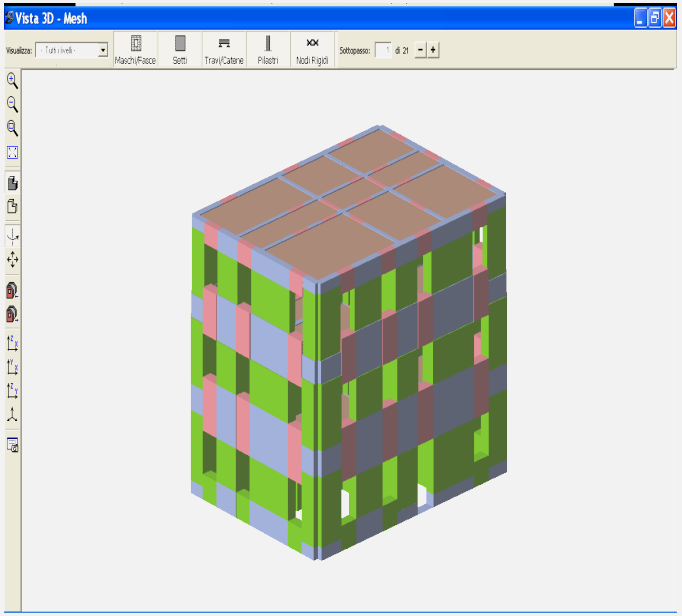
STRONG SPANDRELS
WEAK PIERS

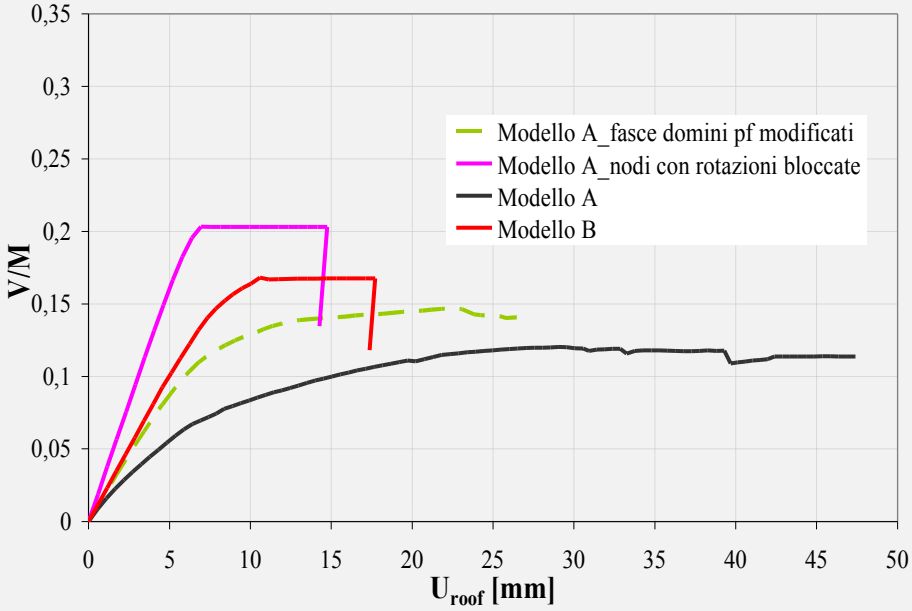
NON LINEAR PUSHOVER ANALYSIS





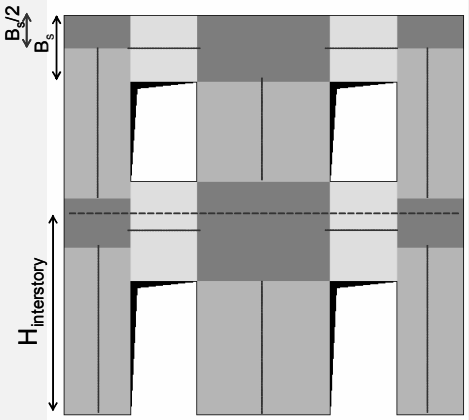
TREMURI Program (ask to tremuri@gmail.com – commercial release: www.stadata.com)
3D modelling of masonry buildings by the equivalent frame model.





3-D EQUIVALENT FRAME MODEL

- Identification of the geometry of piers, spandrels and rigid nodes

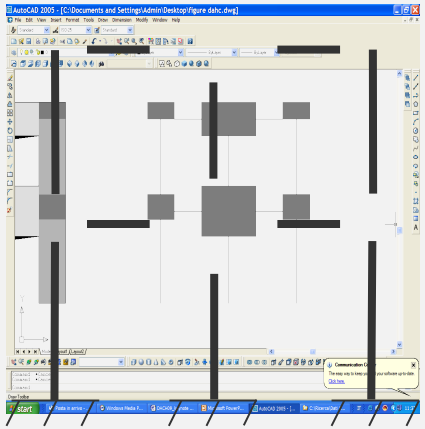


Element axis

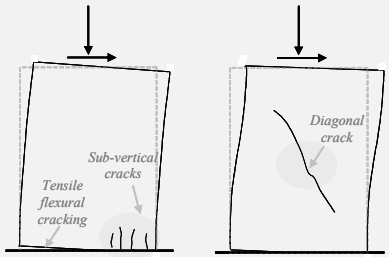
Pier

Spandrel

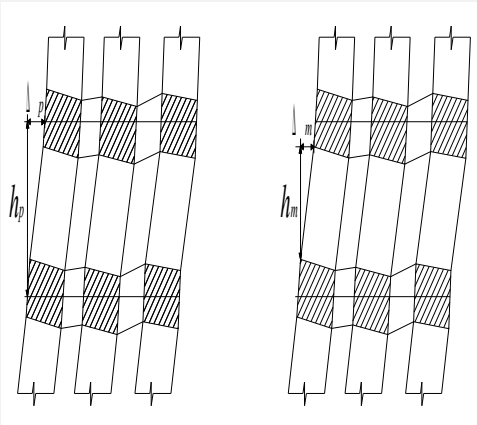
Rigid node



Nonlinear beam or macroelement



- Ductility control in terms of drift limits



Drift limits defined as a function of the failure mode occurred

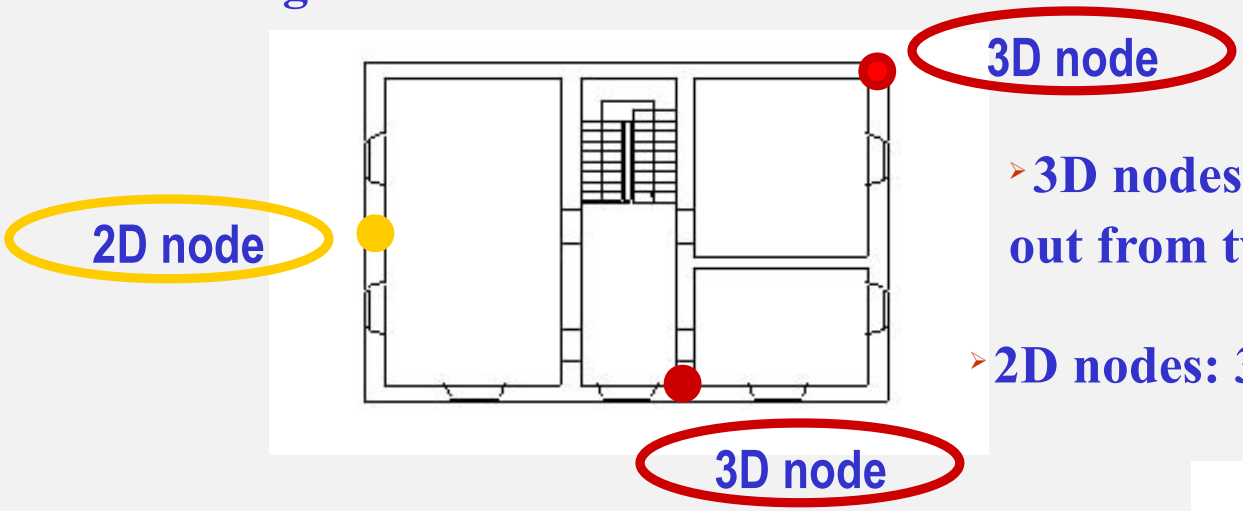
$$\delta_m^{DL} = \frac{\Delta_m}{h_m} = \delta_u \begin{cases} 0.004 & \text{Shear} \\ 0.006\text{-}0.008 & \text{Rocking} \end{cases}$$

Shear failure

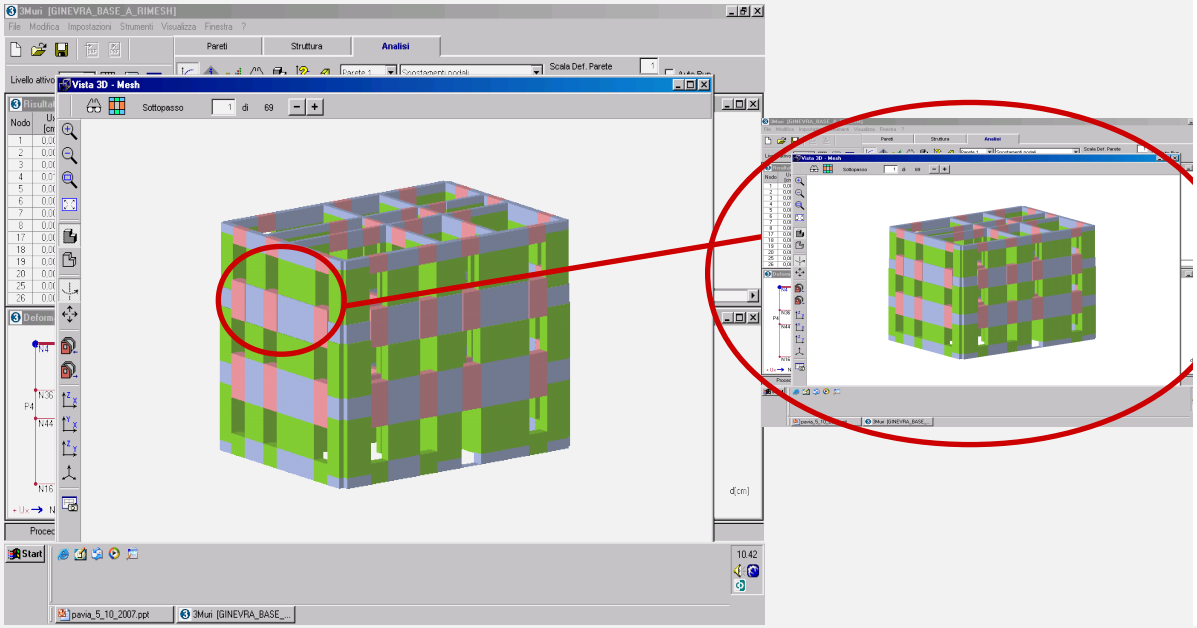
Rocking failure

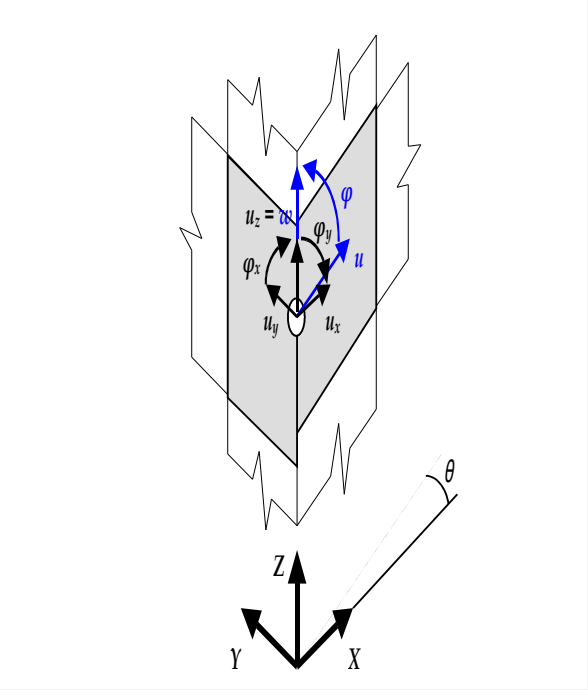
3-D EQUIVALENT FRAME MODEL

Assembling 2D walls



- 3D nodes: 5 d.o.f ✳ they come out from two 2D nodes
- 2D nodes: 3 d.o.f. in the wall plane



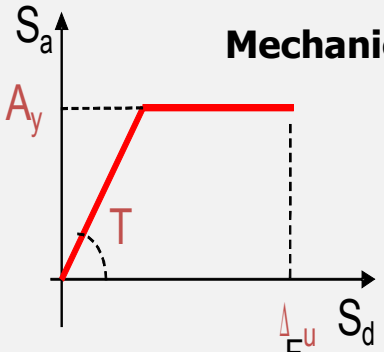


WP6 – MODELS FOR VULNERABILITY ASSESSMENT

Methods for the assessment at territorial scale by the performance based approach

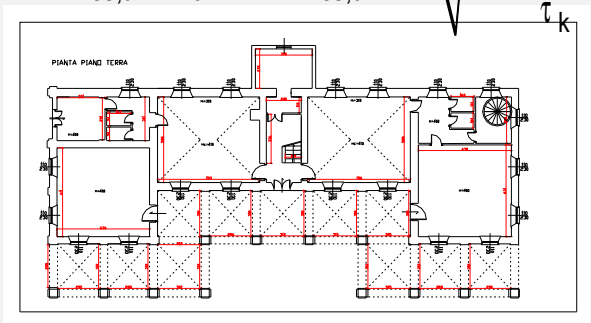
PALACES

Mechanical models

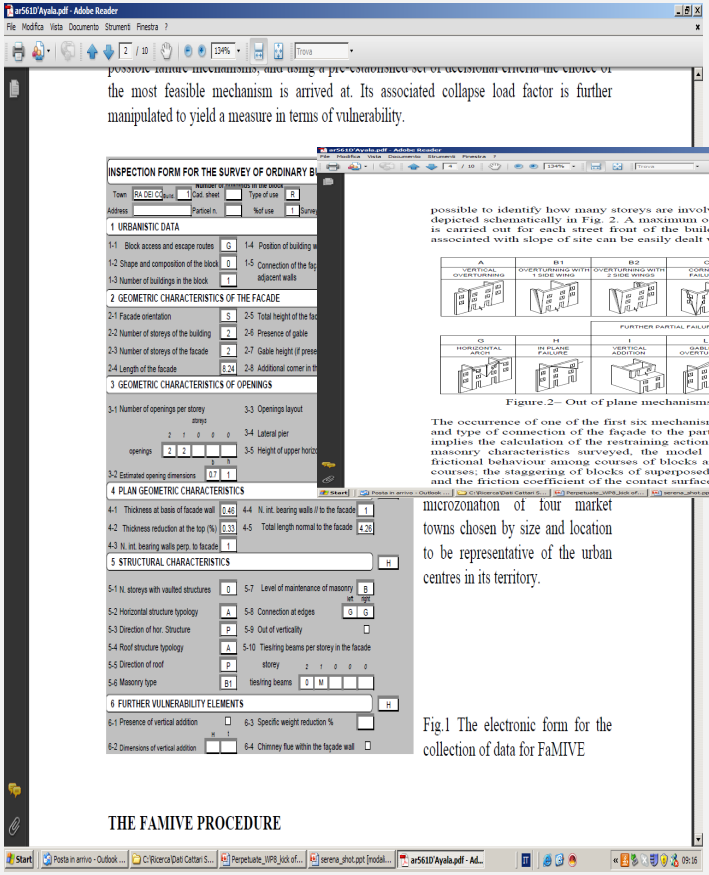


$$A_{y,dir} = \frac{F_{dir}}{m^* \Gamma}$$

$$F_{dir} = \xi X A_{res,dir} X \tau_u = \xi X A_{res,dir} X \tau_k \sqrt{1 + \frac{\sigma_{0,dir}}{\tau_k}}$$



FAMIVE Procedure



the most feasible mechanism is arrived at. Its associated collapse load factor is further manipulated to yield a measure in terms of vulnerability.

INSPECTION FORM FOR THE SURVEY OF ORDINARY BU

1 URBANISTIC DATA

2 GEOMETRIC CHARACTERISTICS OF THE FACADE

3 GEOMETRIC CHARACTERISTICS OF OPENINGS

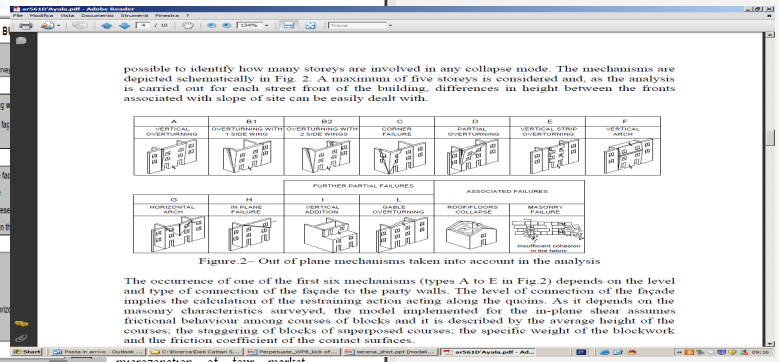
4 PLAN GEOMETRIC CHARACTERISTICS

5 STRUCTURAL CHARACTERISTICS

6 FURTHER VULNERABILITY ELEMENTS

Fig.1 The electronic form for the collection of data for FaMIVE

THE FAMIVE PROCEDURE

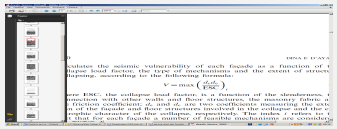


possible to identify how many storeys are involved in any collapse mode. The mechanisms are depicted schematically in Fig. 2. A maximum of five storeys is considered and, as the analysis is carried out for each street front of the building, differences in height between the fronts associated with slope of site can be easily dealt with.

Figure.2– Out of plane mechanisms taken into account in the analysis

The occurrence of one of the first six mechanisms (types A to E in Fig.2) depends on the level and type of connection of the façade to the party walls. The level of connection of the façade implies the calculation of the restraining action acting along the quoins. As it depends on the masonry characteristics surveyed, the model implemented for the in-plane shear assumes frictional behaviour among courses of blocks and it is described by the average height of the courses; the staggering of blocks of superposed courses; the specific weight of the blockwork and the friction coefficient of the contact surfaces.

microzonation of four market towns chosen by size and location to be representative of the urban centres in its territory.



D'Ayala & Speranza 2002

UBATH - University of Bath – D. D'Ayala

UNIGE - University of Genoa – S. Lagomarsino

WP7 – APPLICATION TO CASE STUDIES

TASK 8.2: Application to the Citadel and the Great Mosque of

TASK 8.3: Application to the historical centre of Rhodes (Gre

WP7 – APPLICATION TO CASE STUDIES

TASK 8.4: Application to the case studies damaged by L'Aquila

TASK 8.5: Application to the St. Pardo Cathedral in Larino (Molise Region, Italy)

TASK 8.6: Application to the Kolizej Palace in Ljubljana

CONCLUSIONS

- High seismic vulnerability of ancient masonry structures
- Need of mechanical models and seismic analysis procedures (non linear static and dynamic)
- Need of experimental tests, in particular on shaking table
- Effectiveness of displacement-based assessment
- Guidelines for the adoption of conservative strengthening interventions, traditional or innovative

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