EARTHQUAKE PLANNING AND PROTECTION ORGANIZATION (E.P.P.O.)

COUNCIL OF EUROPE
EUROPEAN CENTRE ON PREVENTION AND FORECASTING OF EARTHQUAKES (E.C.P.F.E.)

TRAINING COURSE ON SEISMIC RISK ASSESSMENT IN SPECIFIC AREAS WITH MONUMENTAL STRUCTURES

Athens - December 6-10, 2010

Vulnerability models for the seismic risk assessment of monuments

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The seismic vulnerability 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

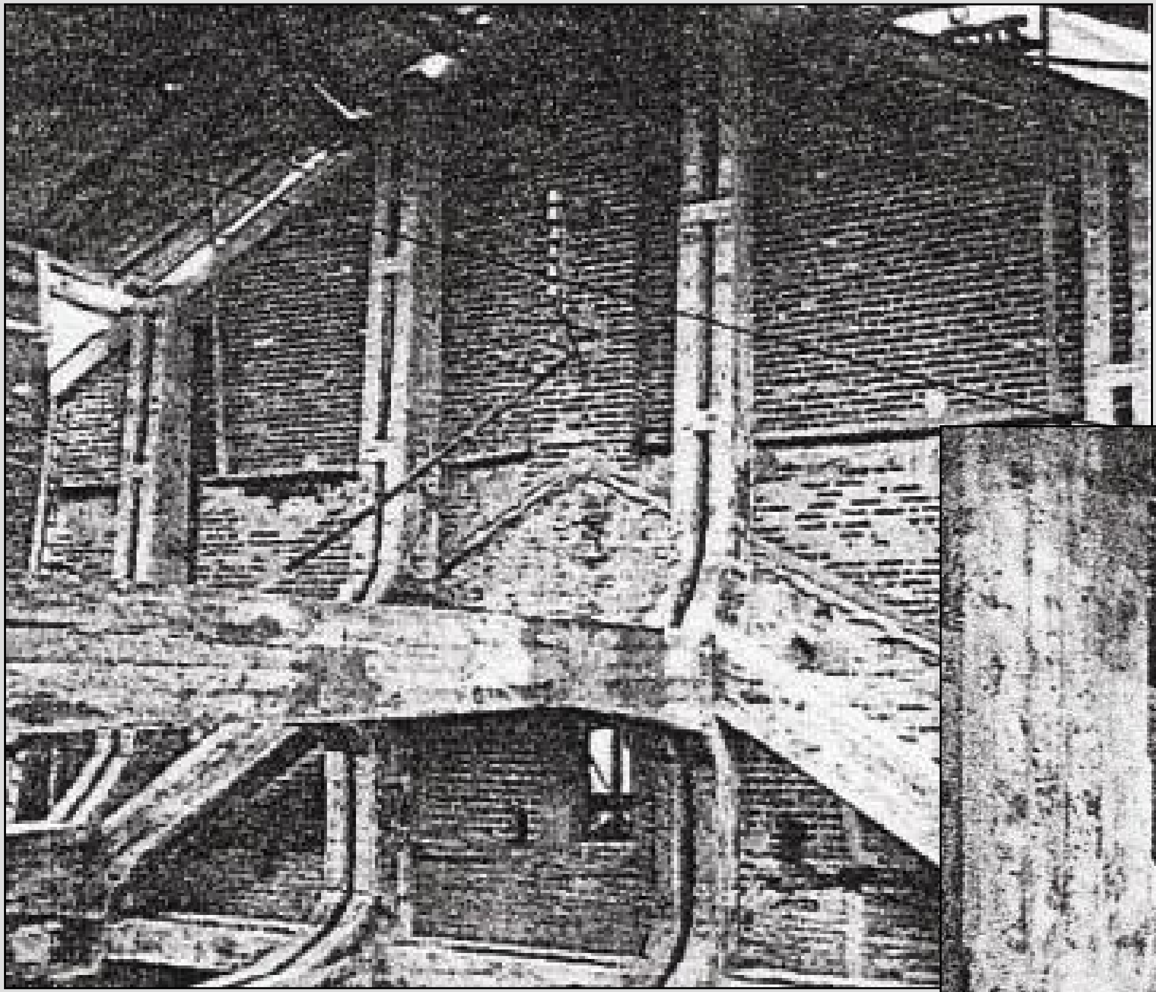
ORDINARY BUILDINGS:

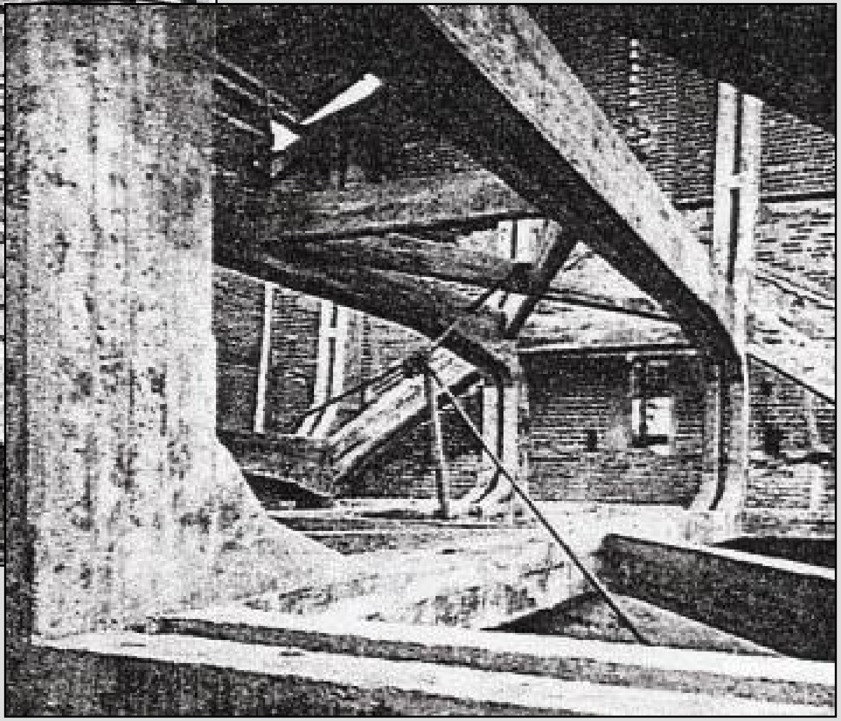
New masonry buildings must be in confined masonry. In repairing existing damaged buildings it is necessary to insert r.c. ring beams and vertical columns inside the masonry walls.

MONUMENTAL STRUCTURES:

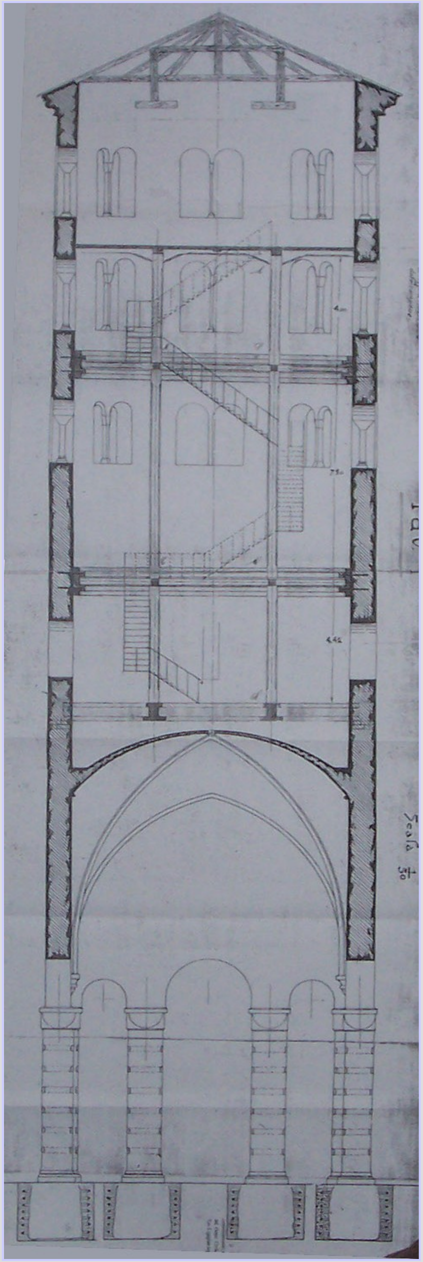
The code states the criteria of “case by case” (nothing is mandatory for monu-ments). However, in most cases the requirements of safety came first of that of conservation. A lot of interventions with r.c. elements were used in the XX century.

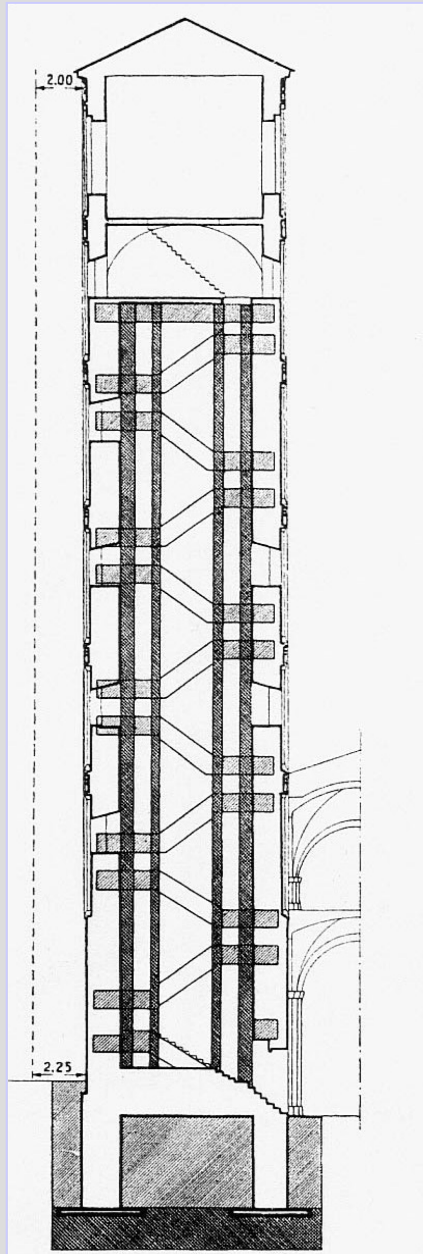
CHIESA DI S. ANDREA, VERCELLI – A. GIBERTI,1926.

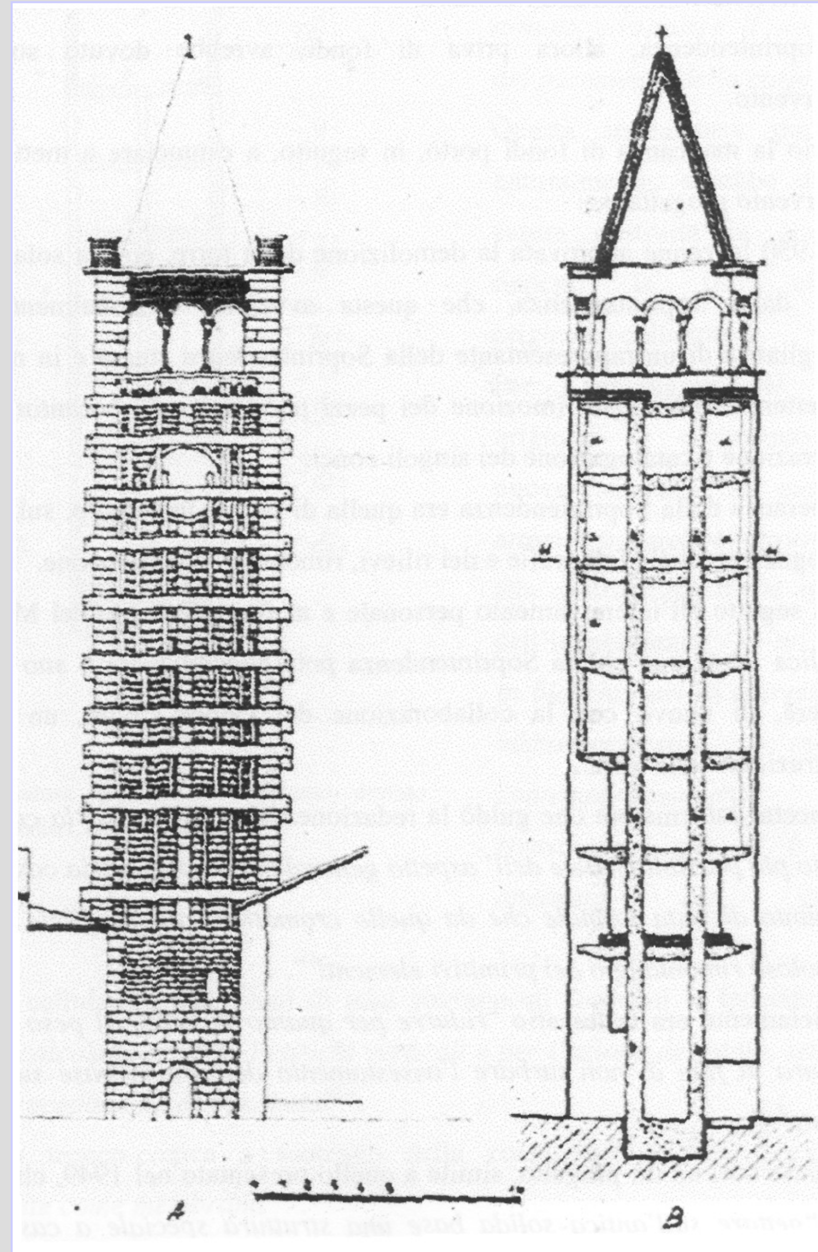




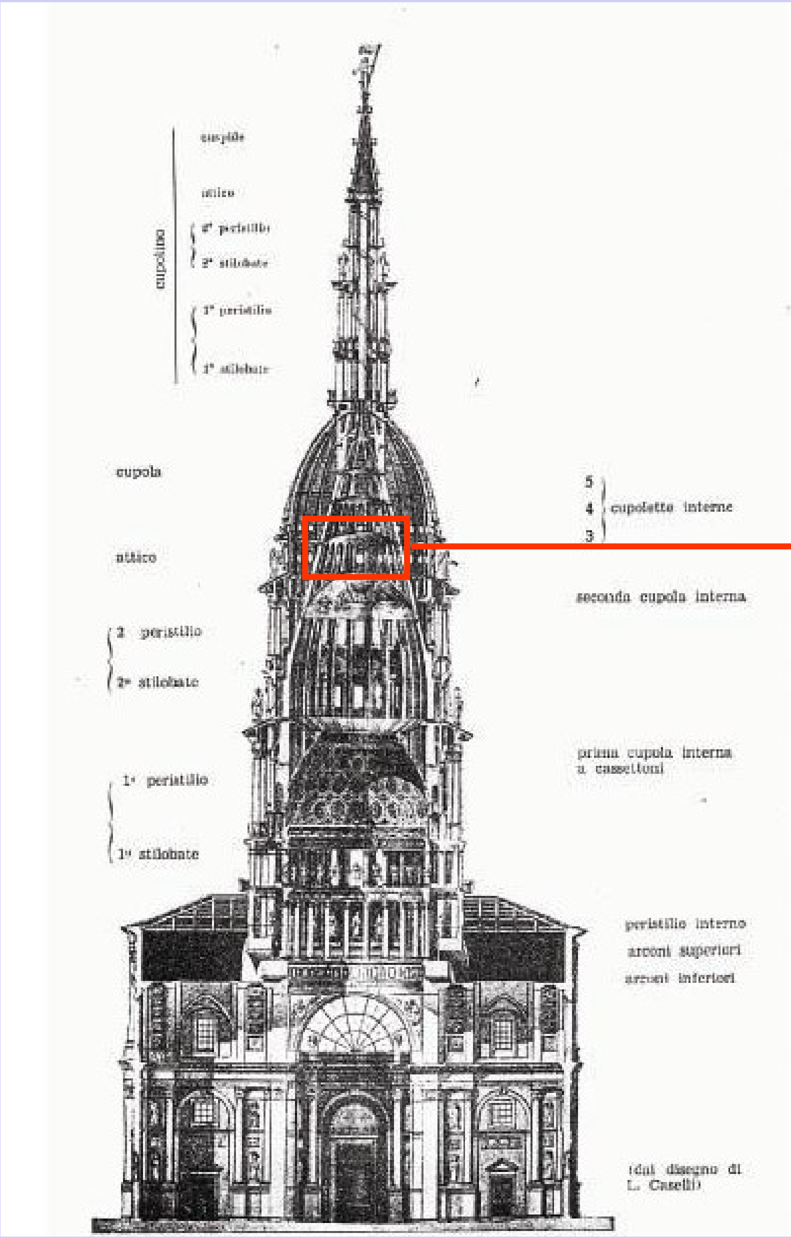
TOWERS

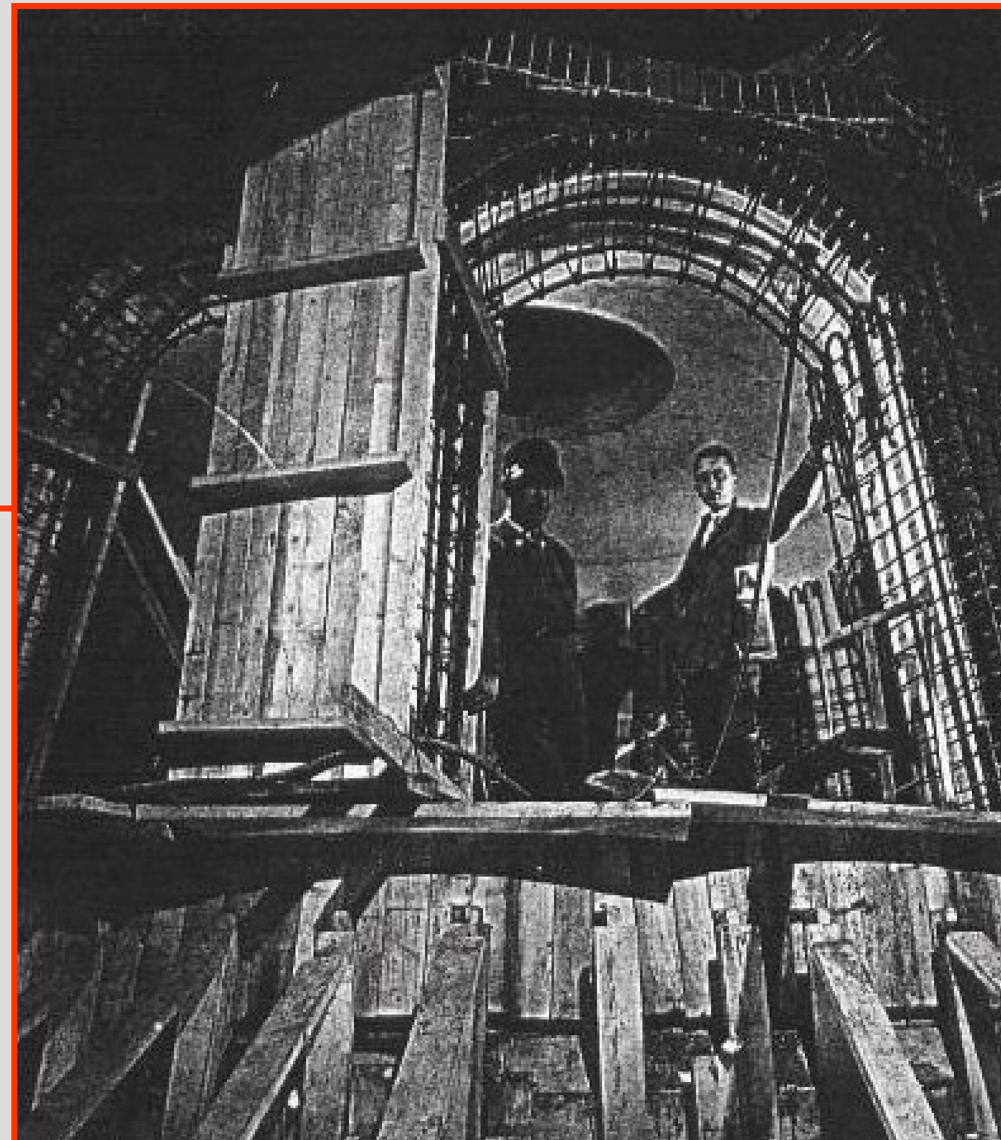






BASILICA DI SAN GAUDENZIO, NOVARA – A. DANUSSO, 1930-1945





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

IRPINIA EARTHQUAKE (1980)

Magnitude 7

- 3000 casualties
- 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

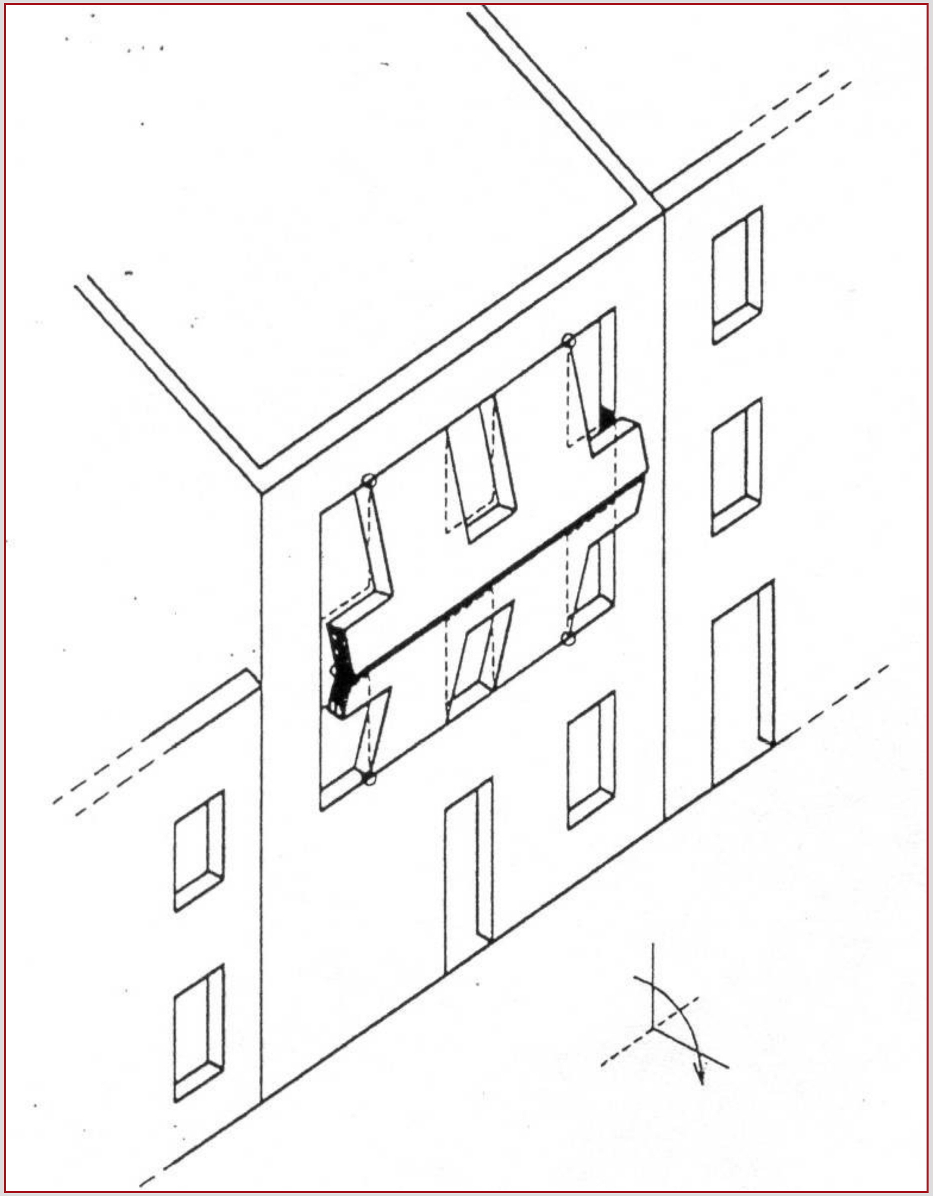
The earthquake proof (Umbria 1997)

After two big earthquakes (Friuli 1976, Irpinia 1980), the Italian seismic code proposed to apply systematically for the retrofitting of existing masonry buildings the concepts of confined masonry or of the new generation of masonry buildings: r.c. stringcourses and vertical elements inside masonry, substitution of flexible and light timber floors and roofs with heavy and stiff r.c. slabs.

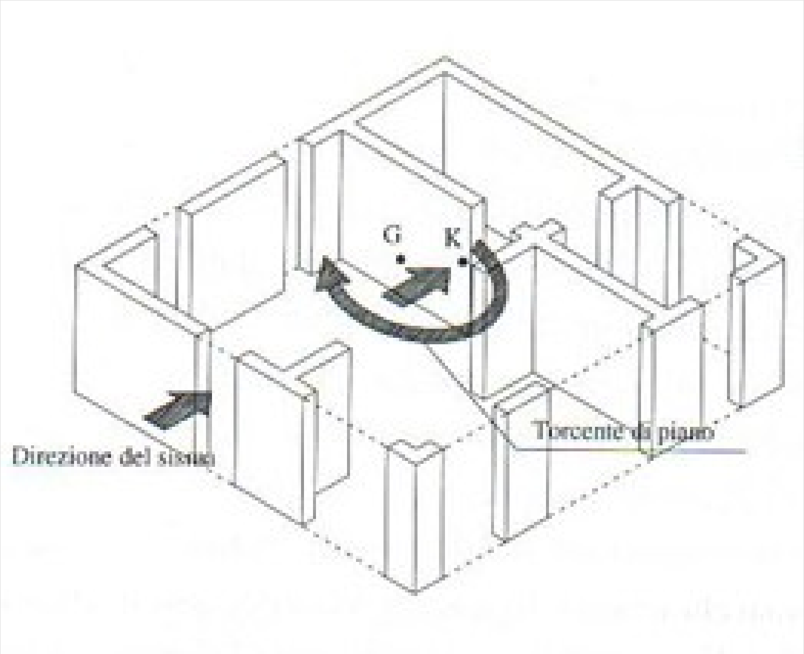
Wide preventive actions were funded by government in many regions, after some small earthquakes.

The negative effect of this approach appeared evident in the Umbria earthquake (1997).

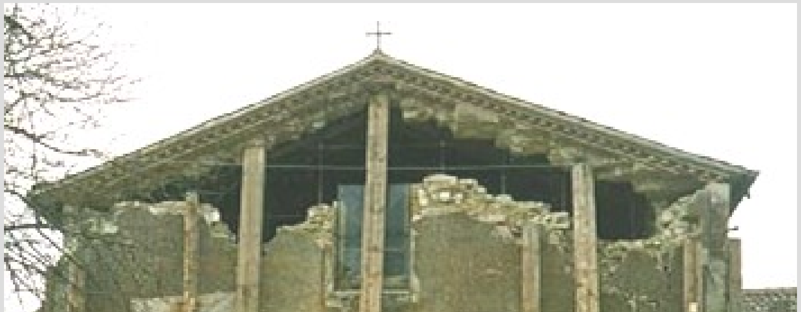
Insertion of r.c. ring beams and change of timber floors with r.c. slabs

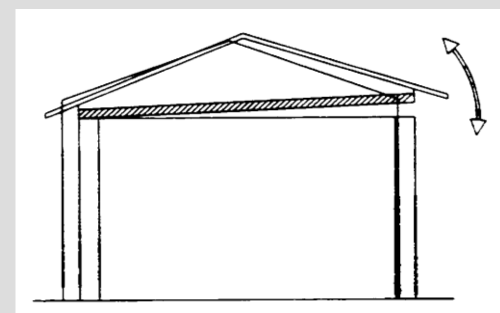


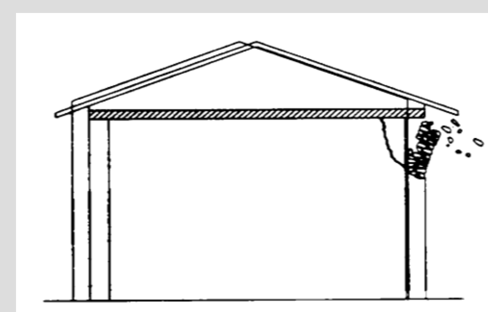
Increase of masses at roof level and torsional effects due to rigid floors



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







The damage assessment: a lesson to learn

S. Maria Assunta in Montesanto, Sellano

L’AQUILA EARTHQUAKE – April 6, 2009

S. Maria del Suffragio Church
(named Church of Anime Sante)

Spanish Fortress

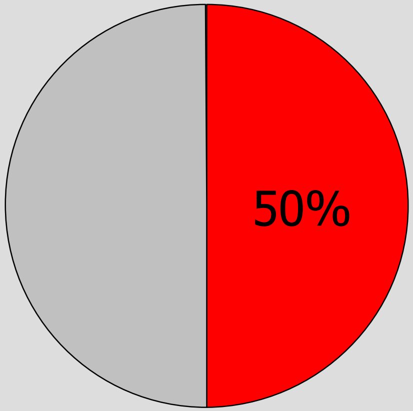
Saint Maximus Cathedral

Saint Maximus Cathedral

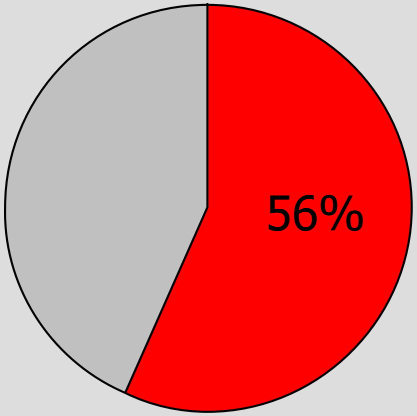
Damage assessment to monuments in L'Aquila

- NUMBER MONUMENTS CONSIDERED: 48

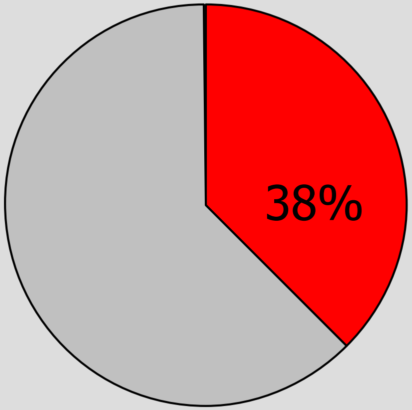
TOTAL



L'AQUILA TOWN



OUT OF L'AQUILA

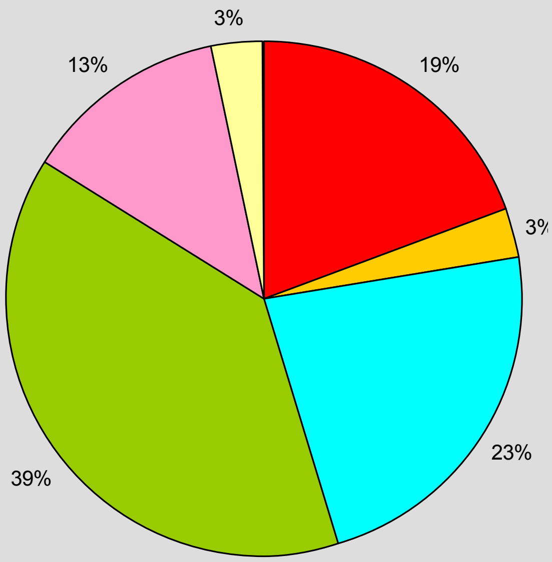


■ Buildings subjected to modern strengthening interventions

PREVALENT PERIOD: end of '60 – beginning of '70

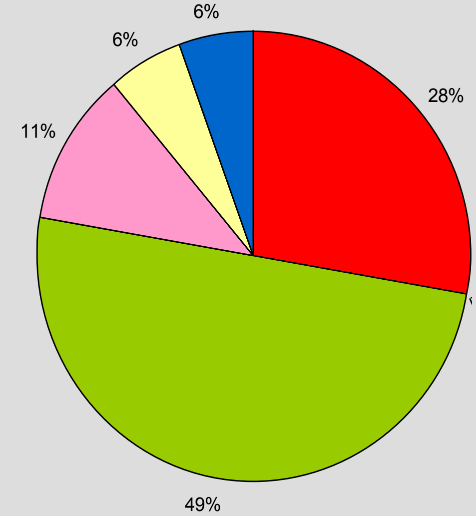
Damage assessment to monuments in L'Aquila

- TYPE OF STRENGTHENING INTERVENTIONS

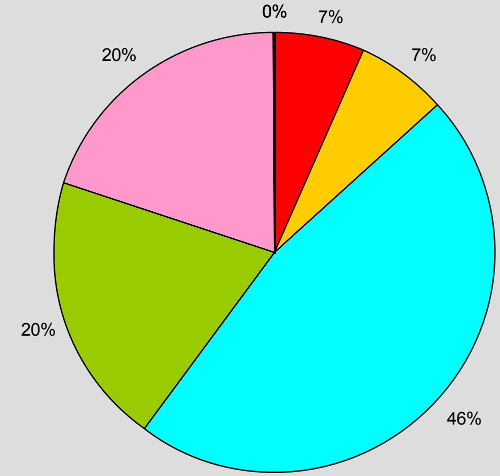


- R.C. ROOFS
- STEEL ROOFS
- R.C. OR STEEL FLOORS
- R.C. RING BEAMS
- R.C. FRAMES
- FRP WRAPPING

CHURCHES



PALACES



BASILICA OF SANTA MARIA DI COLLEMAGGIO – L'AQUILA

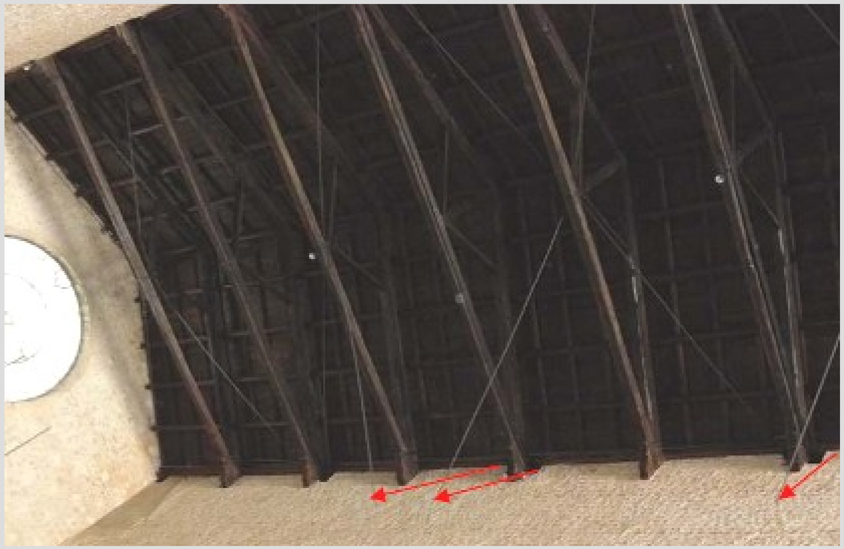
1918-21 **Strengthening of masonry in the backside of the façade by means of a r.c. cantilever beams; insertion of r.c. ring beams in the lateral walls.**

1960-1962 **Rebuilt of the dome and the vaults of the transept in r.c.; r.c. ring beams.**

1970-1972 **Demolishing of the baroque wooden-beam ceilings and elevation of 3 meters of the lateral walls of the central nave, with r.c. ring beams at the top.**

1998 **Steel bracings (cross tie rods) in the roof, under the king trusses, with dissipative elements.**

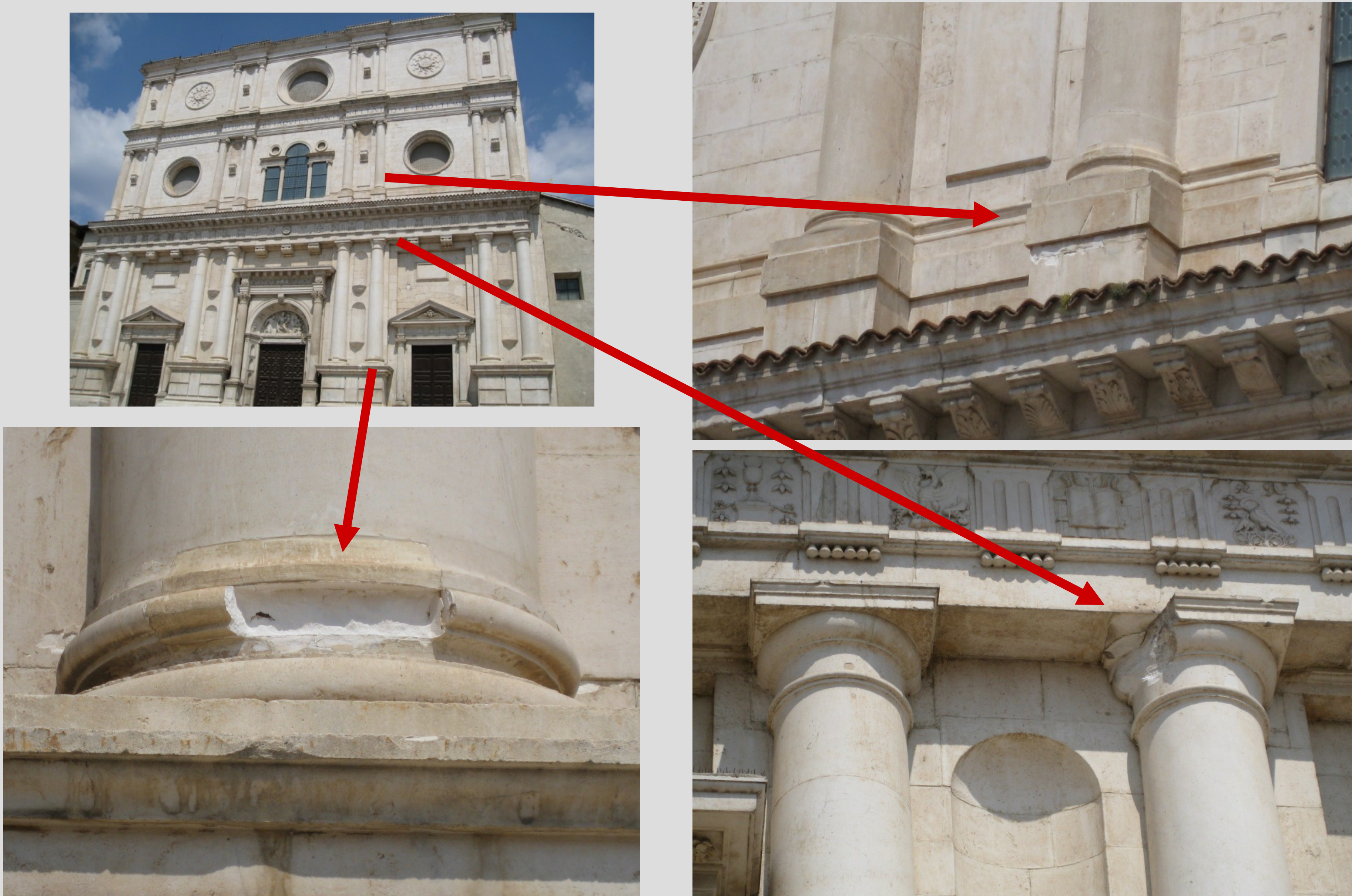
BASILICA OF SANTA MARIA DI COLLEMAGGIO – L'AQUILA



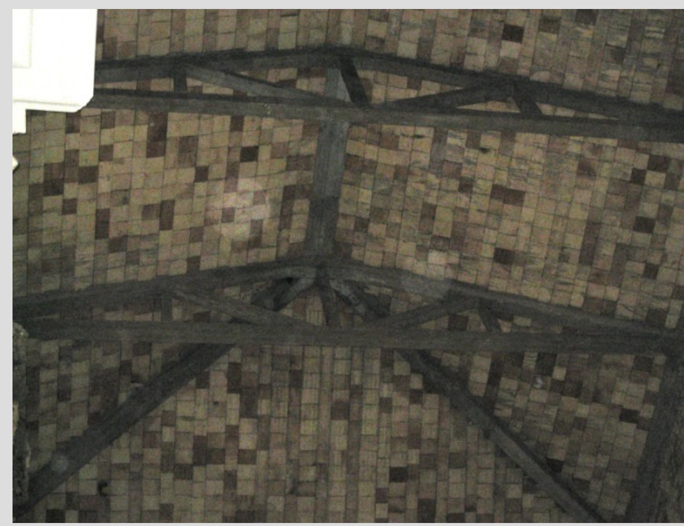
San Bernardino Church – L’Aquila

San Bernardino Church – L'Aquila



San Domenico Church – L'Aquila

New r.c. roof
(1960/70)



SAINT FELIX MARTYR CHURCH – POGGIO PICENZE

New r.c. roof in the transept (1960/70)
(all other roofs are in timber and the only vault that collapsed is in the transept)

SANTA MARGHERITA CHURCH - L'AQUILA

Thick R.C. slab over the barrel vault of the nave.

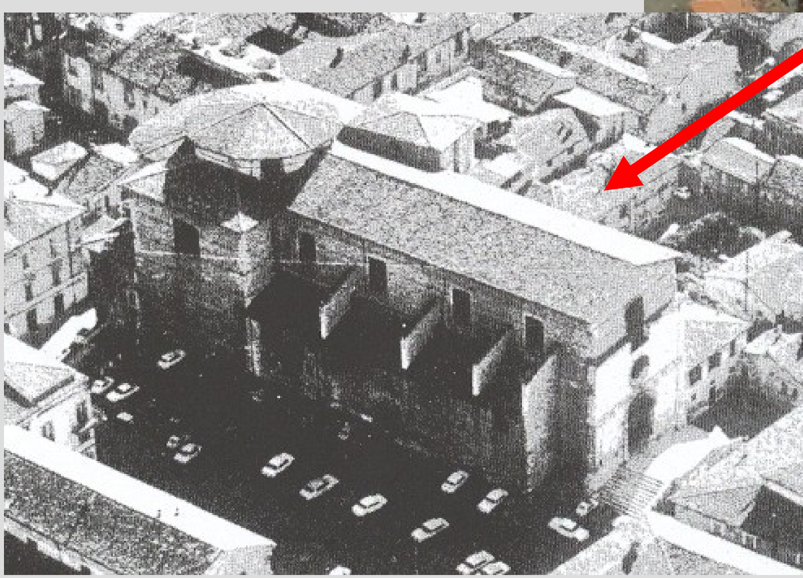
Out of plane shear failure of the lateral walls.

SAINT STEFANO TOWER
Santo Stefano di Sessanio

SAINT MARCUS CHURCH – L'AQUILA

Strengthening of the triumphal arch by FRP (2007)

SANTA MARIA PAGANICA CHURCH



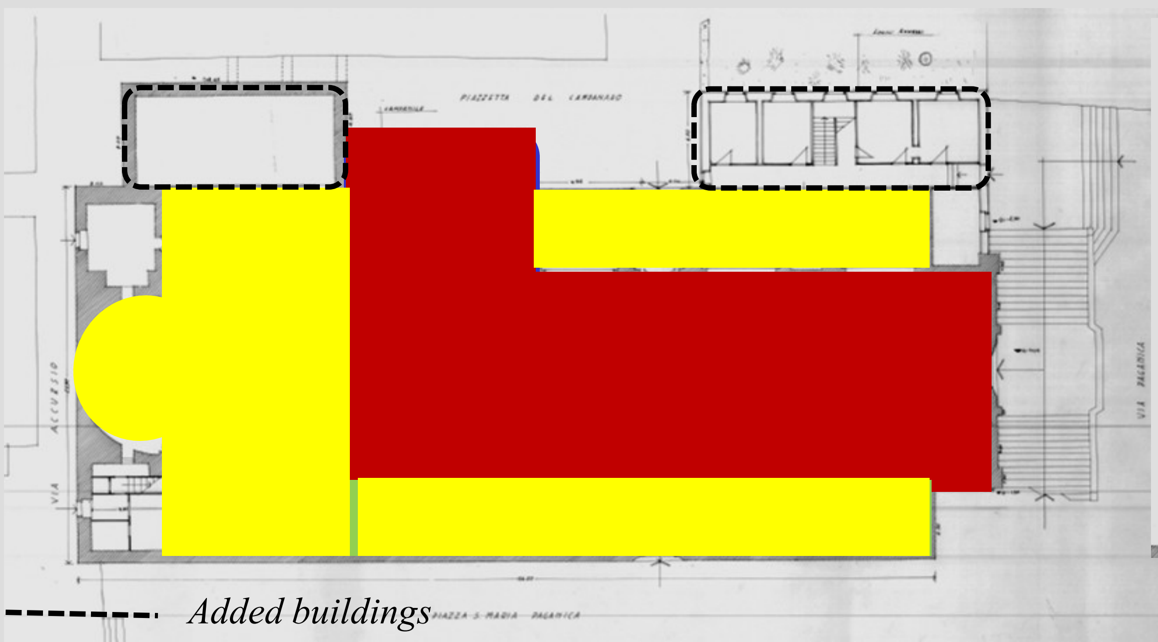
Interesting aspects:

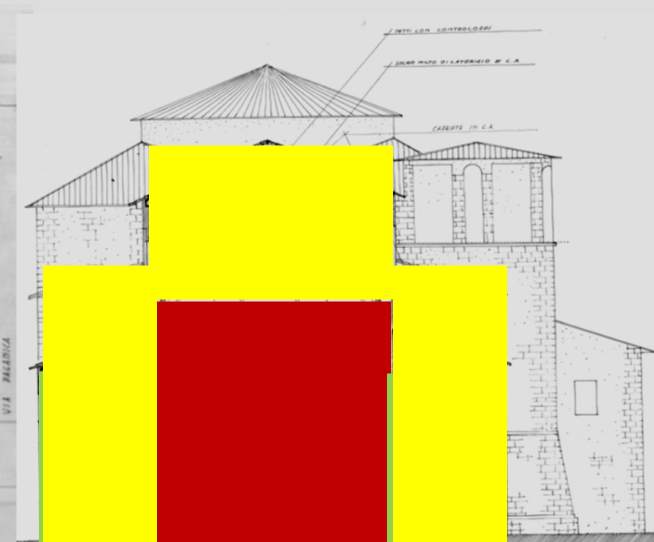
- historical transformations
- wide dimensions
- modern retrofitting

COLLAPSE SEQUENCE AND PROVISIONAL INTERVENTIONS

BRIEF HISTORICAL NOTES

- ✓ Built in the XIII century with a single nave, close to an ancient tower;
- ✓ Small aisles were added to the single original nave before 1703;
- ✓ After the earthquake in 1703, the church was extended and raised up (see the façade); external butresses were added, which closed the aisles and created lateral chapels;
- ✓ In the Sixties, the wooden roof was replaced by a reinforced concrete roof (precast trusses and steel tie-rods), with a thick and heavy r.c. slab.

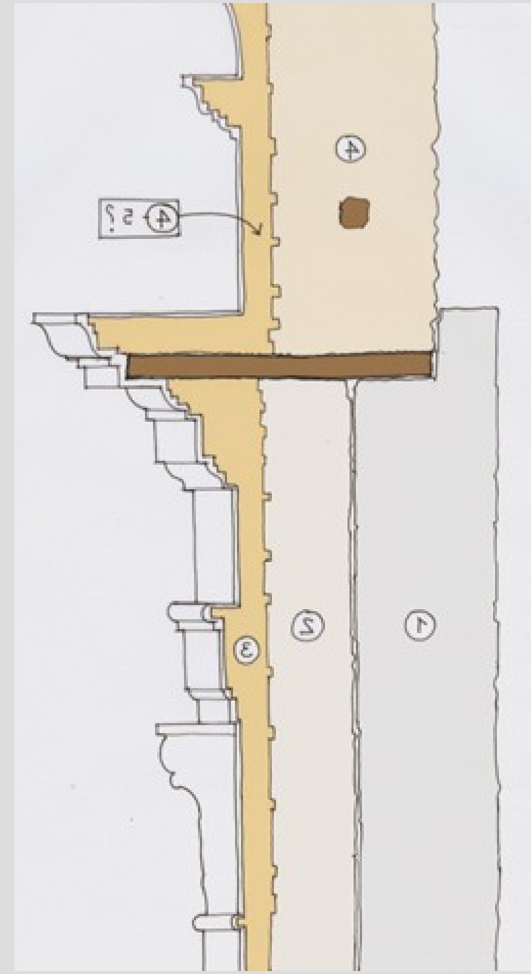


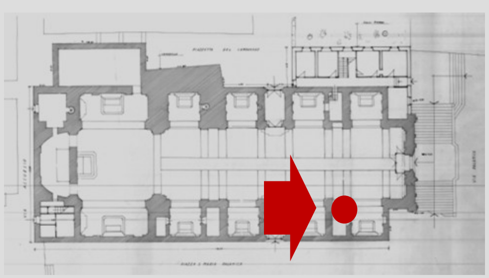


CONSTRUCTIVE DETAILS

The collapse allows to see the internal masonry and the constructive details.

CONSTRUCTIVE DETAILS





The subsequent transformations and the poor quality of connections increased the vulnerability of lateral walls.

CONSTRUCTIVE DETAILS

Dome, vaults in the transept, the apse and the lateral chapels were in brick masonry, whereas the barrel vault in the nave was a wattle vault.

In the dome there are wooden elements arranged at 45 degrees.

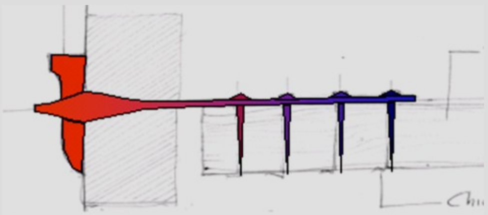
CONSTRUCTIVE DETAILS

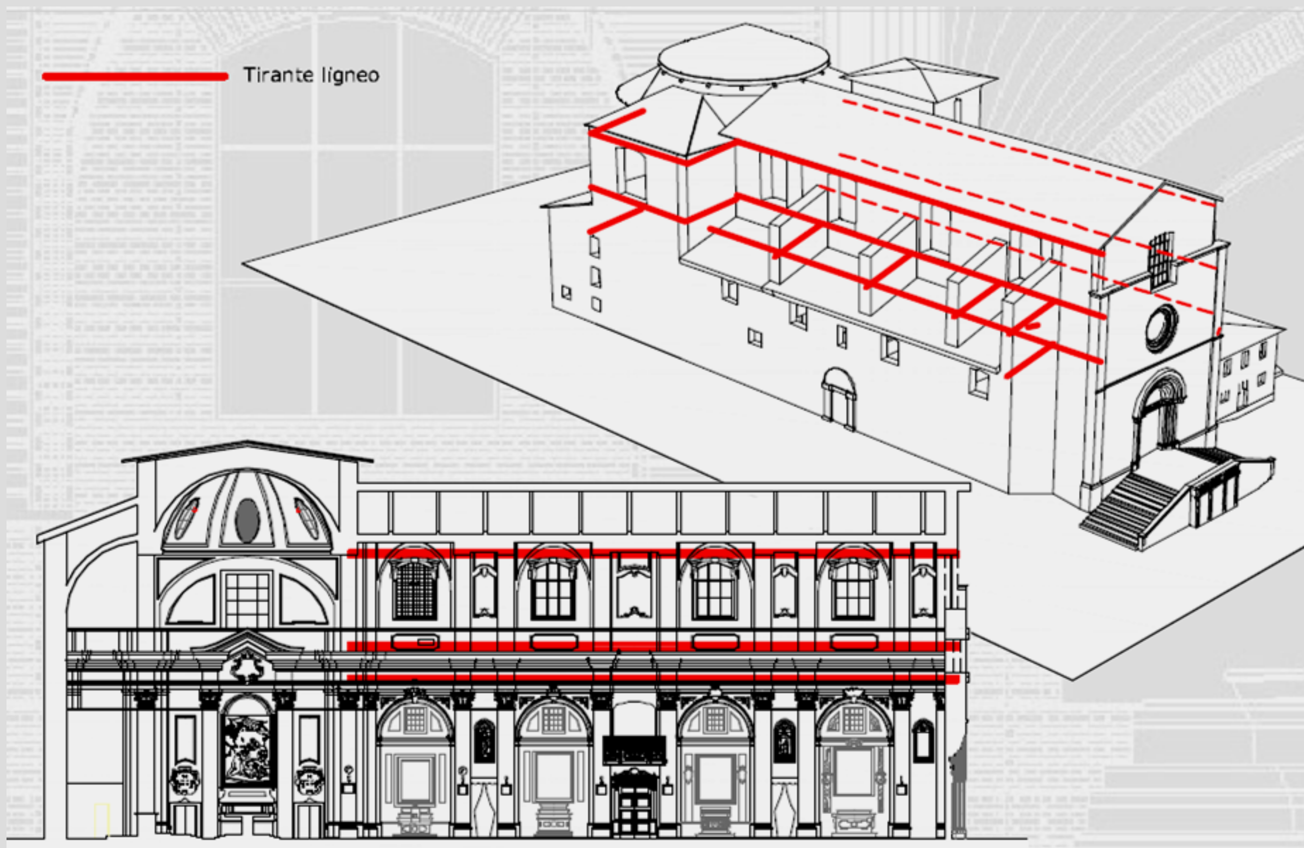
CONSTRUCTIVE DETAILS

The insertion of wooden logs inside masonry was a rule-of-art very used in L'Aquila after the earthquake in 1703.

CONSTRUCTIVE DETAILS

The insertion of wooden ties inside masonry was a rule-of-art very used in L'Aquila after the earthquake in 1703.





MAIN COLLAPSE MECHANISMS

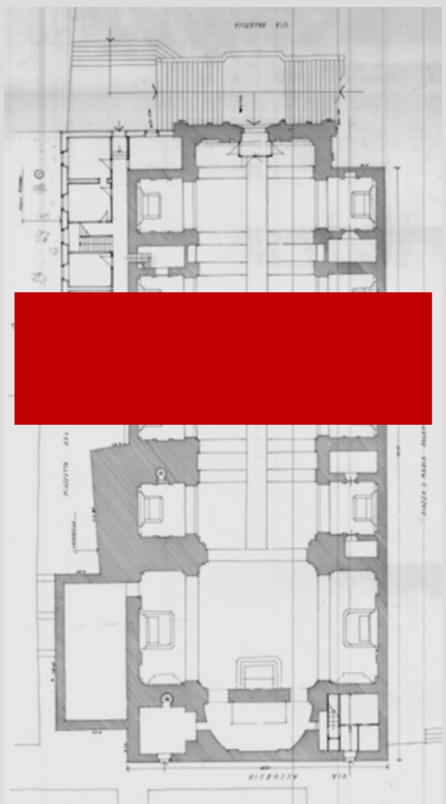
Overturning of the façade:

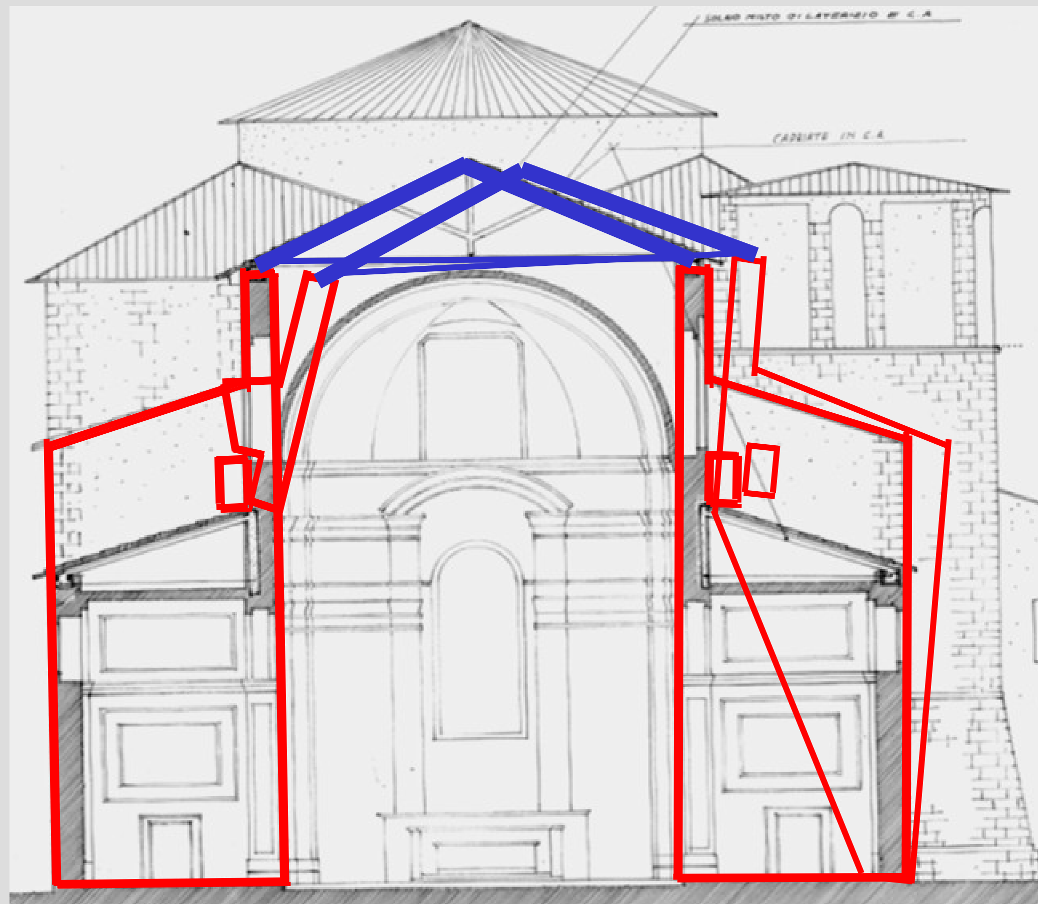
April 15, 2009

May 15, 2009

MAIN COLLAPSE MECHANISMS

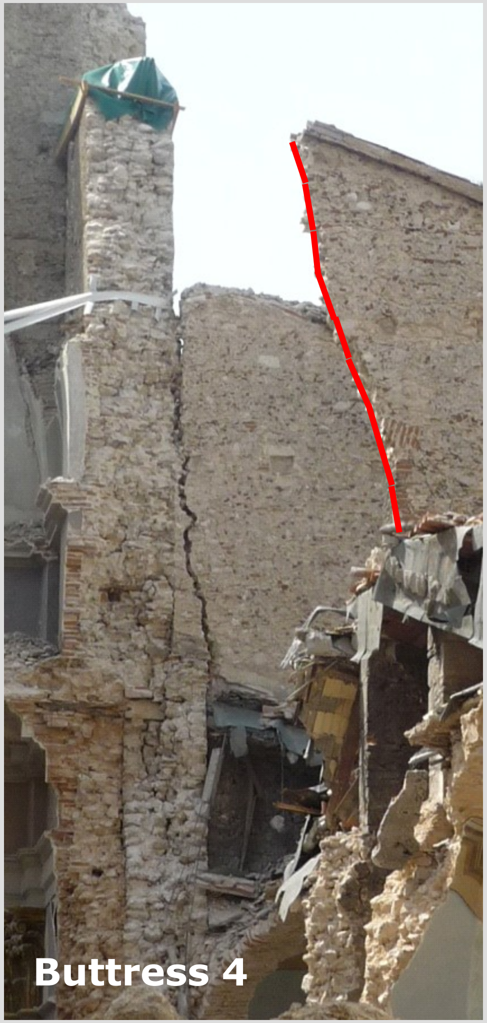
- The original wooden trusses roof coupled displacements at top of the walls
- The new roof had a steel tie which behaves only in tension
- During earthquake: 1) increase of traction force in the steel ties (possible failure) due to different displacements and vertical component; 2) sliding of r.c. ring beam
- The presence of the tower increase the difference of displacements

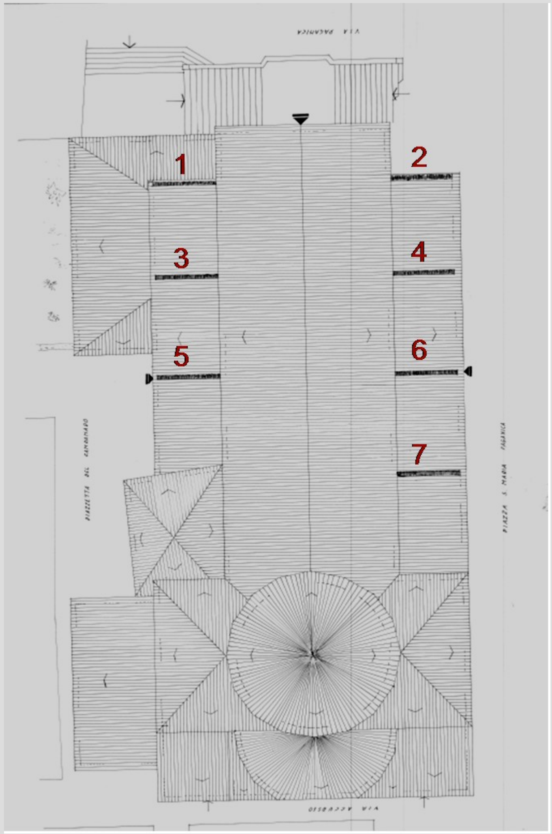




MAIN COLLAPSE MECHANISMS

Nave’s transversal response:





CONSTRUCTIVE DETAILS

The roof was rebuilt in the Sixties with r.c. trusses and steel ties.

r.c. ring beam

CONSTRUCTIVE DETAILS

The roof was rebuilt in the Sixties with r.c. trusses and steel ties.

precast trusses and steel tie-rods

heavy concrete slab

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:

- singling out of 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 actual 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,….)

NEW ITALIAN SEISMIC CODE AND GUIDELINES

Ministry of Cultural Heritage – Law n° 42, 22.1.2004
“Code for the preservation of cultural heritage and landscape”

Ministry of Infrastructures and Trasportation – DM 14.1.2008
(GU n.29 del 4.2.2008, suppl.ord. N. 30)
“Technical code for the design of civil constructions”

Ministry of Infrastructures and Trasportation – Circ. 2.2.2009, n. 617
Instructions for the application of the “Technical code for the design of civil constructions”

Directive of the Prime Minister – 12 ottobre 2007
(Ministry of Cultural Heritage - Ministry of Infrastructures and Trasportation – Civil Protection Department)
(GU n.25 del 29.1.2008, suppl.ord. N. 24)
“Guidelines for evaluation and mitigation of seismic risk to cultural heritage”

Council of Public Works - Ministry of Infrastructures and Trasportation
Approved on July 23, 2010 (N. 92)
New “Guidelines for evaluation and mitigation of seismic risk to cultural heritage”, in line with the “Technical code for the design of civil constructions” 2008

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

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

The seismic assessment of masonry structures

Vulnerability assessment of monuments at territorial scale

LV1: analisys by means of simplified mechanical or statistically based models

Design of restoration intervention (evaluation on a single monument)

LV2: evaluation on single macroelements (design of local interventions)

LV3: evaluation of the seismic response of the whole construction (design of a global restoration intervention)

$$I_S = \frac{a_{SLU}}{\gamma_I S a_g}$$

SAFETY INDEX

NOMINAL LIFE (reference period)

VULNERABILITY OF THE CULTURAL HERITAGE

In many Italian seismic areas there is a high number of historic monuments
It is worth to evaluate their vulnerability at a territorial scale.

Vulnerability model: correlation between the HAZARD and the DAMAGE

HAZARD	VULNERABILITY MODEL
MACROSEISMIC INTENSITY	OBSERVATIONAL (MACROSEISMIC)
PGA and SPECTRAL VALUES	MECHANICAL

LAGOMARSINO S. (2006). On the vulnerability assessment of monumental buildings. Bulletin of Earthquake Engineering, Vol. 4.4, ISSN 1570-761X, Springer Netherlands, pp. 445-463.

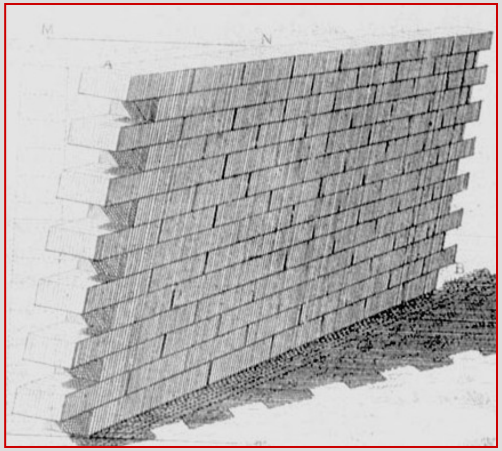
Lagomarsino S. (2006). Chapter 7 - Vulnerability assessment of historical buildings. In *Assessing and Managing Earthquake Risk* (Sousa Oliveira C., Roca A., Goula X. Eds.), Springer.

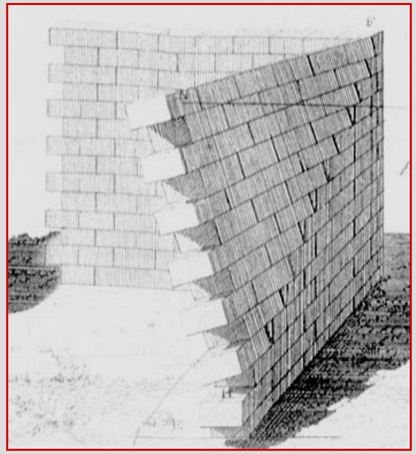
OBSERVATIONAL VULNERABILITY

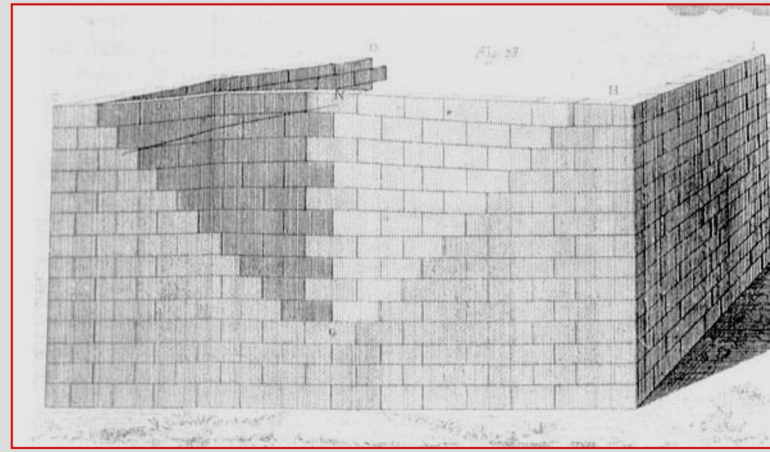
The damage assessment to monumental buildings (in particular churches), after the earthquakes in Italy in the last 30 years (Friuli, 1976; Irpinia, 1980; Umbria and The Marches, 1997; Molise, 2002), provided wide observational information (recurrent behaviour, damage patterns, vulnerability, etc.)

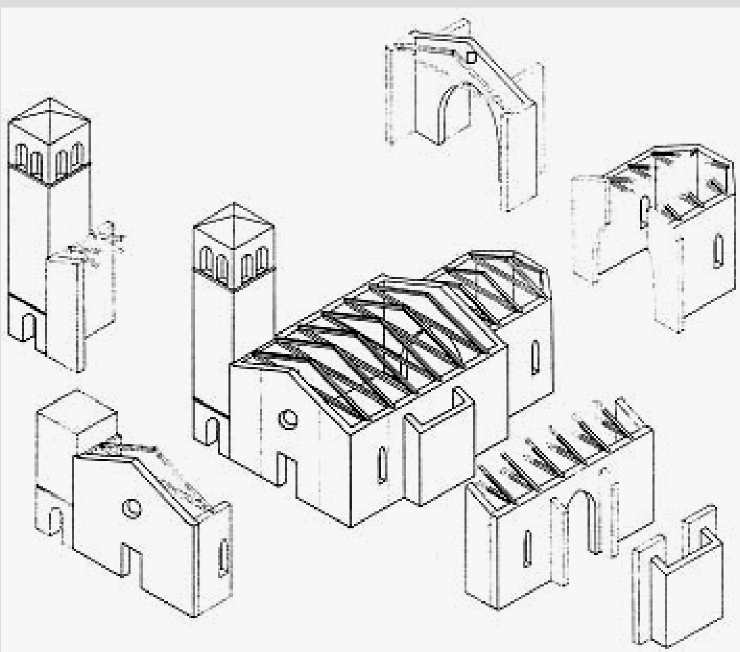
THE DAMAGE ASSESSMENT IN THE EMERGENCY

Elementary collapse mechanisms (from Rondelet)

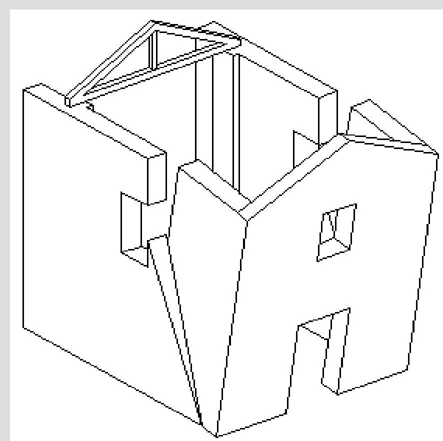


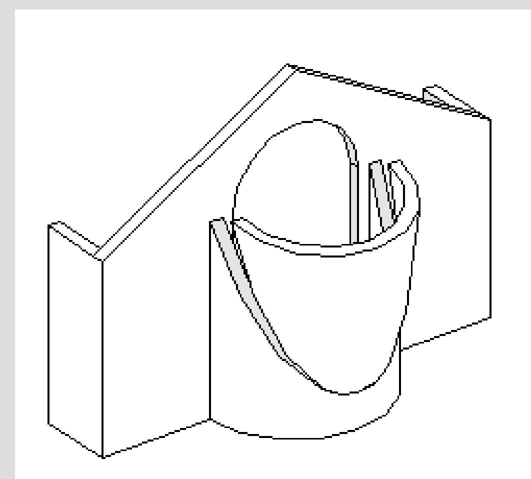




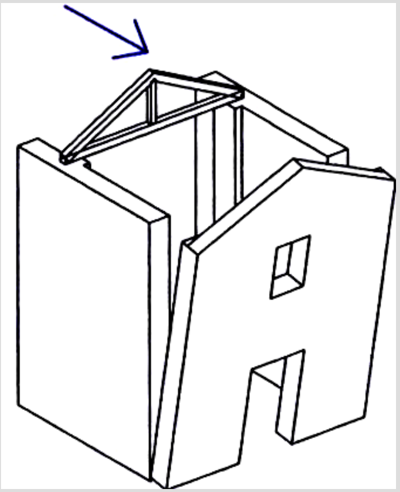


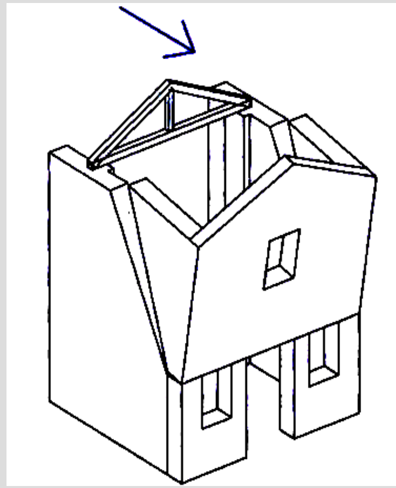
Decomposition in macroelements

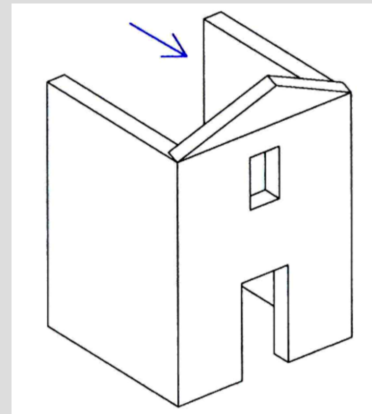


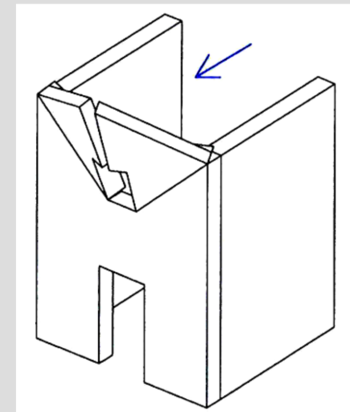


COLLAPSE MECHANISMS IN MACROELEMENTS



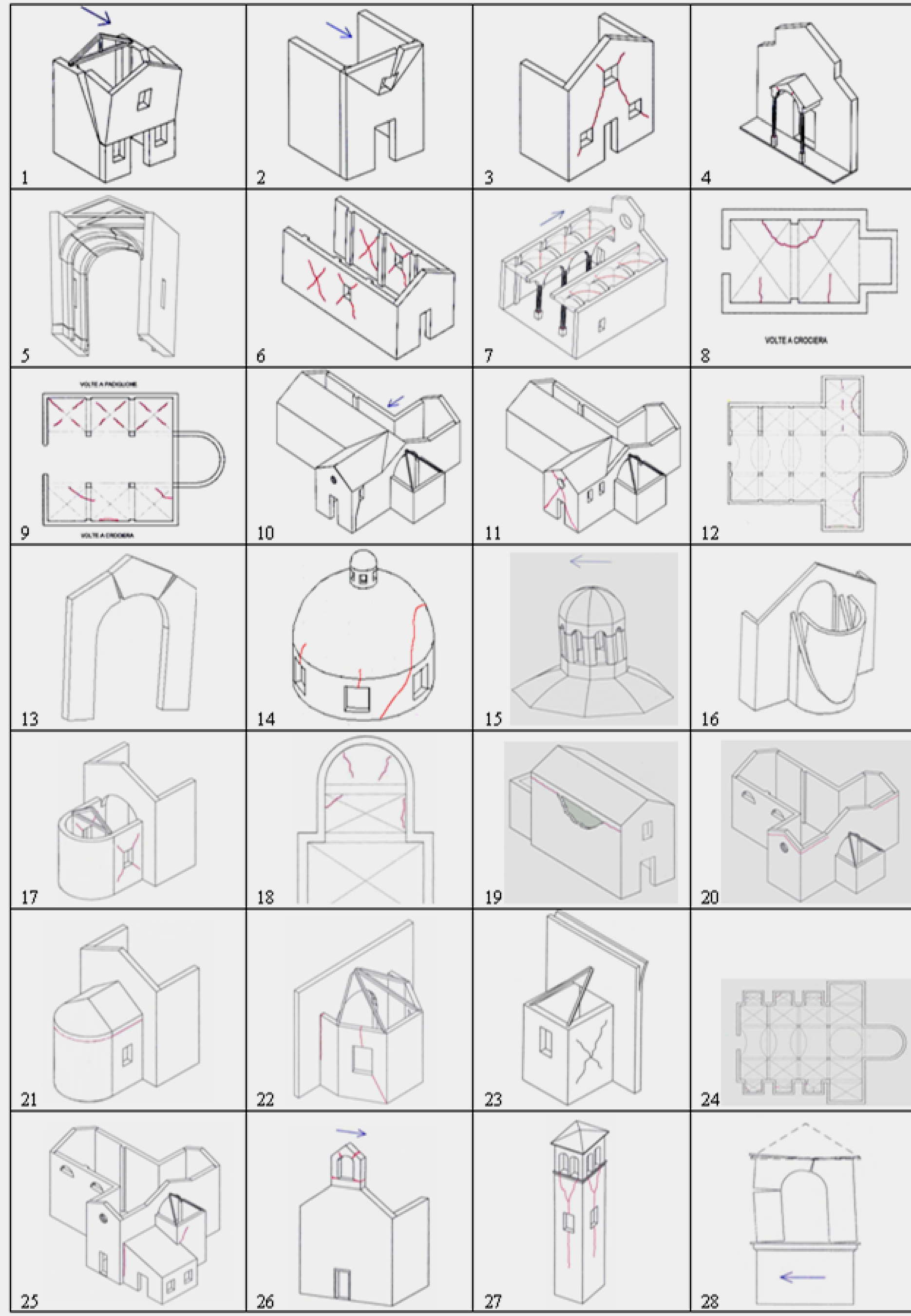






28 COLLAPSE MECHANISMS OF THE FORM FOR DAMAGE AND VULNERABILITY ASSESSMENT OF CHURCHES

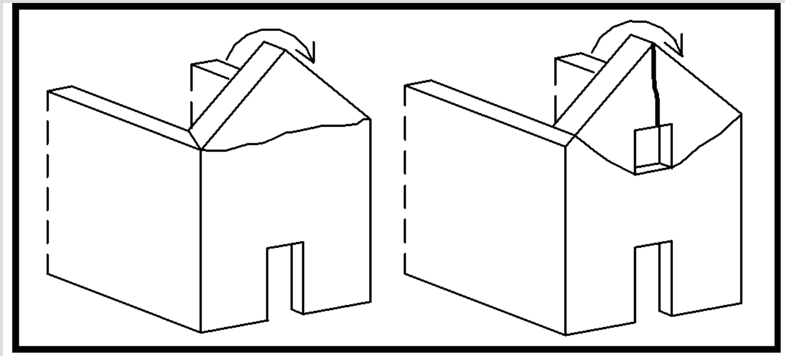
Damage mechanisms	*Macroelement*
1 - OVERTURNING OF THE FAÇADE	FAÇADE
2 - DAMAGE AT THE TOP OF FAÇADE	
3 - SHEAR MECHANISMS IN THE FAÇADE	
4 - NARTEX	
5 - TRANSVERSAL VIBRATION OF THE NAVE	NAVE
6 - SHEAR MECHANISMS IN THE SIDE WALLS	
7 - LONGITUDINAL RESPONSE OF THE COLONNADE	
8 - VAULTS OF THE NAVE	
9 - VAULTS OF THE AISLES	
10 - OVERTURNING OF THE TRANSEPT'S END WALL	TRANSEPT
11 - SHEAR MECHANISMS IN THE TRANSEPT WALLS	
12 - VAULTS OF THE TRANSEPT	
13 - TRIUMPHAL ARCHES	TRIUMPHAL ARCH
14 - DOME AND DRUM	DOME
15 - LANTERN	
16 - OVERTURNING OF APSE	APSE
17 - SHEAR MECHANISMS IN PRESBYTERY AND APSE	
18 - VAULTS IN PRESBYTERY AND APSE	
19 - ROOF MECHANISMS: SIDE WALLS OF NAVE AND AISLES	ROOF COVERING
20 - ROOF MECHANISMS: TRANSEPT	
21 - ROOF MECHANISMS: APSE AND PRESBYTERY	
22 - OVERTURNING OF THE CHAPELS	CHAPEL
23 - SHEAR MECHANISMS IN THE WALLS OF CHAPELS	
24 - VAULTS OF CHAPELS	
25 - INTERACTIONS NEXT TO IRREGULARITIES	
26 - PROJECTIONS (DOMED VAULTS, PINNACLES, STATUES)	BELL TOWER
27 - BELL TOWER	
28 - BELFRY	



THE CHURCH FORM FOR DAMAGE ASSESSMENT

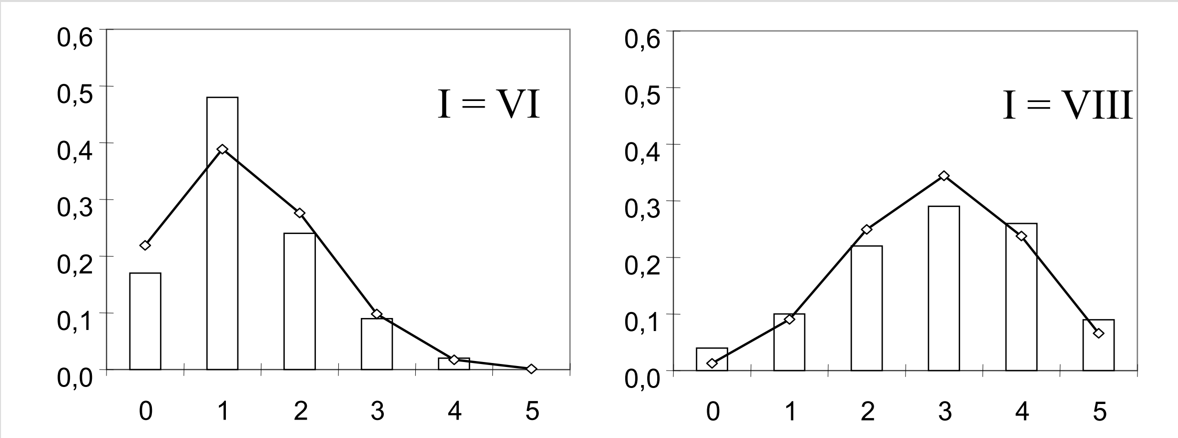
Umbria-Marche earthquake (1997): a methodology for damage and vulnerability assessment (Lagomarsino and Podestà, *Earthquake Spectra*, May 2004)

2. DAMAGE AT THE TOP OF THE FACADE	☐
CRACKS IN THE TOP PART OF THE FACADE	☐☐☐
☐ Facade weakened by wide openings ☐ Lack of a connection with the roof covering	



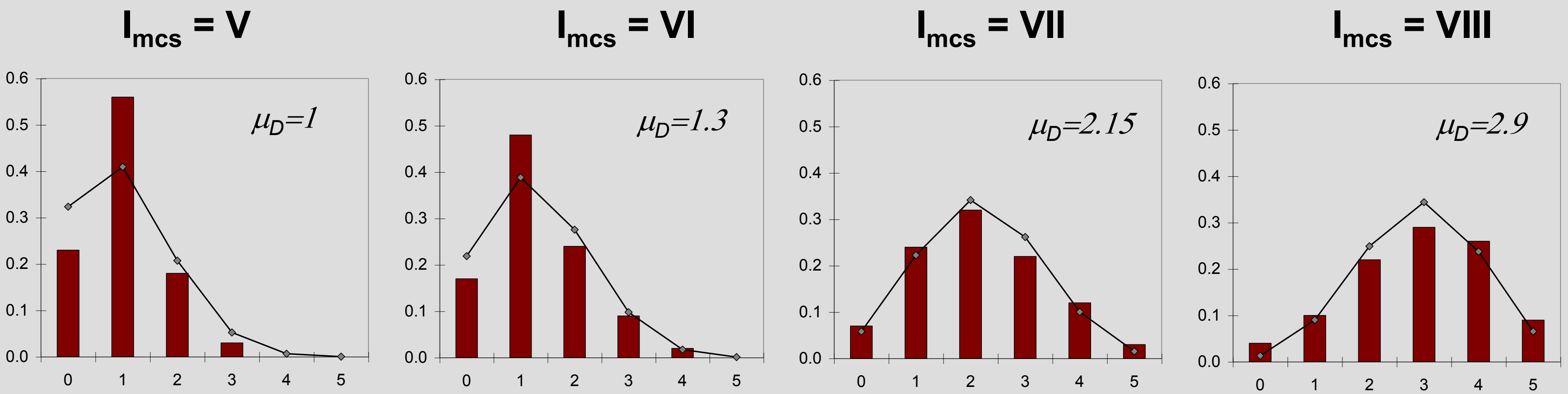
- damage index i_D ($0 < i_D < 1$): mean damage level in macroelements
- vulnerability index i_V ($0 < i_V < 1$): constructive details and aseismic devices

Damage Probability Matrices (DPM)



Macroseismic method

CHURCHES – More than 2000 churches in Umbria and The Marches, have been subdivided in four different groups, depending on the macroseismic intensity.



The damage histograms are fitted very well by a binomial distribution (continuous line), defined by one parameter only: the mean damage grade μ_D

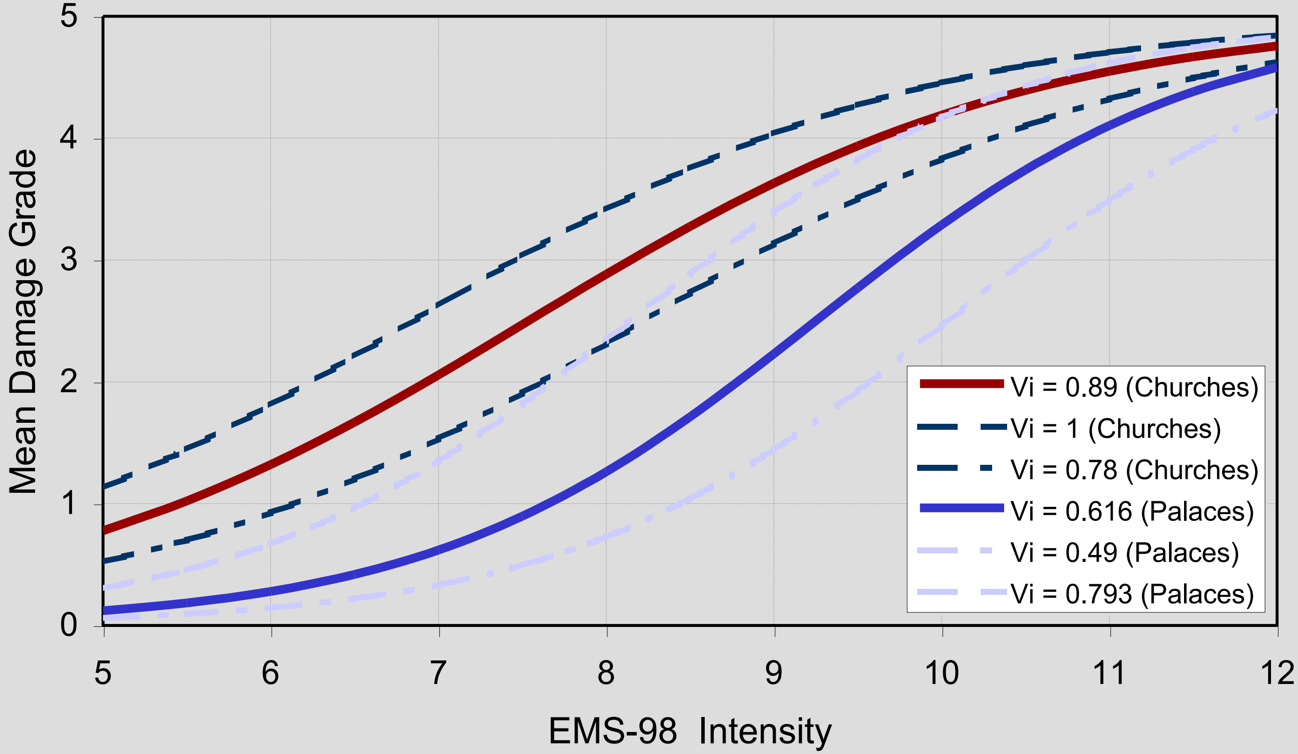
$$p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k \left(1-\frac{\mu_D}{5}\right)^{5-k} \qquad k = (0, 1, 2, 3, 4, 5)$$

Macroseismic method

By means of a statistical analysis of observed damage data, a correlation between the macroseismic intensity I and the mean damage grade μ_D has been obtained for churches and monumental palaces (for palaces, the same analytical relation may be obtained by the definition of EMS'98 scale)

VULNERABILITY CURVES

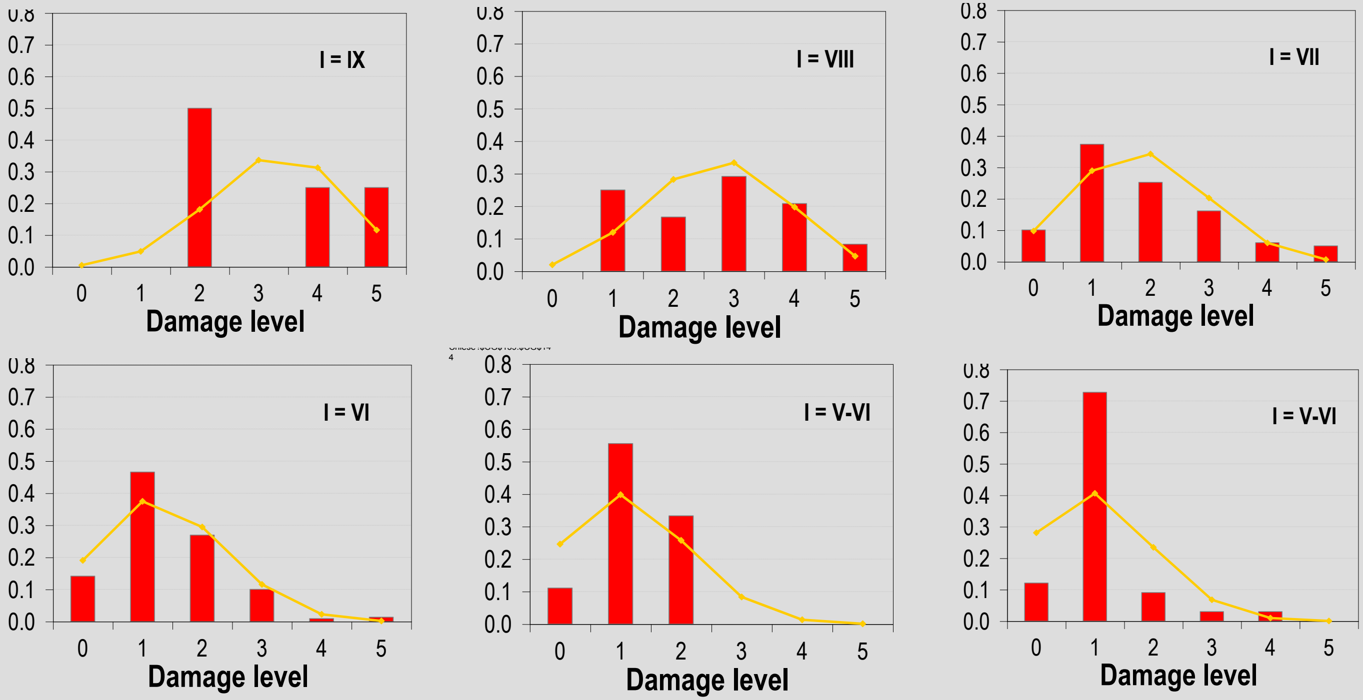
$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I + 6.25 \cdot V - 13.1}{Q} \right) \right]$$



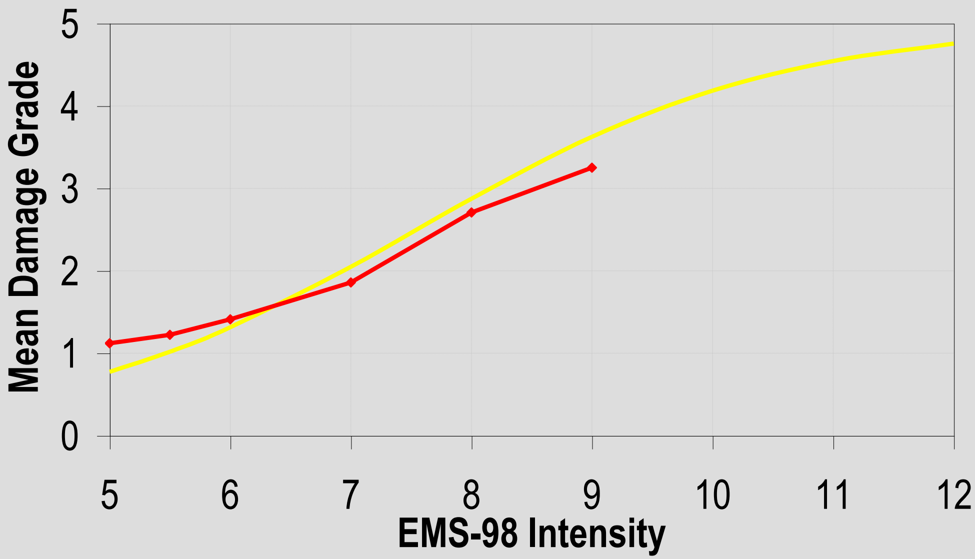
Two parameters:

- vulnerability index V
- ductility index Q

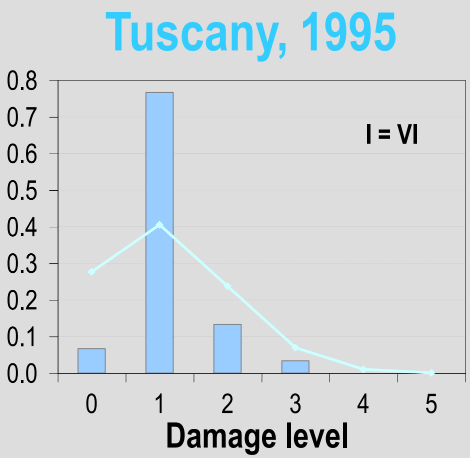
Validation by observed data

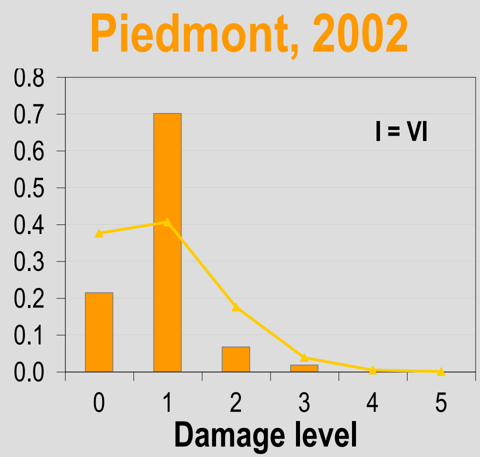


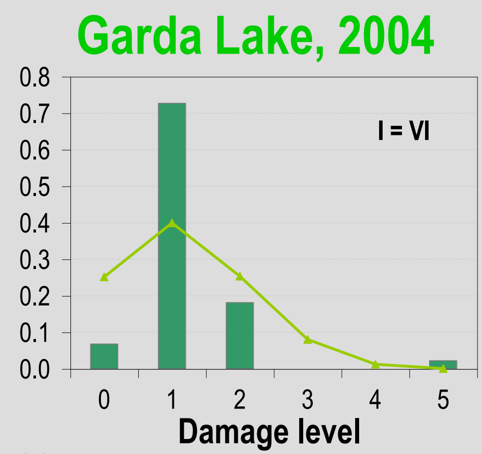
Irpinia, 1980

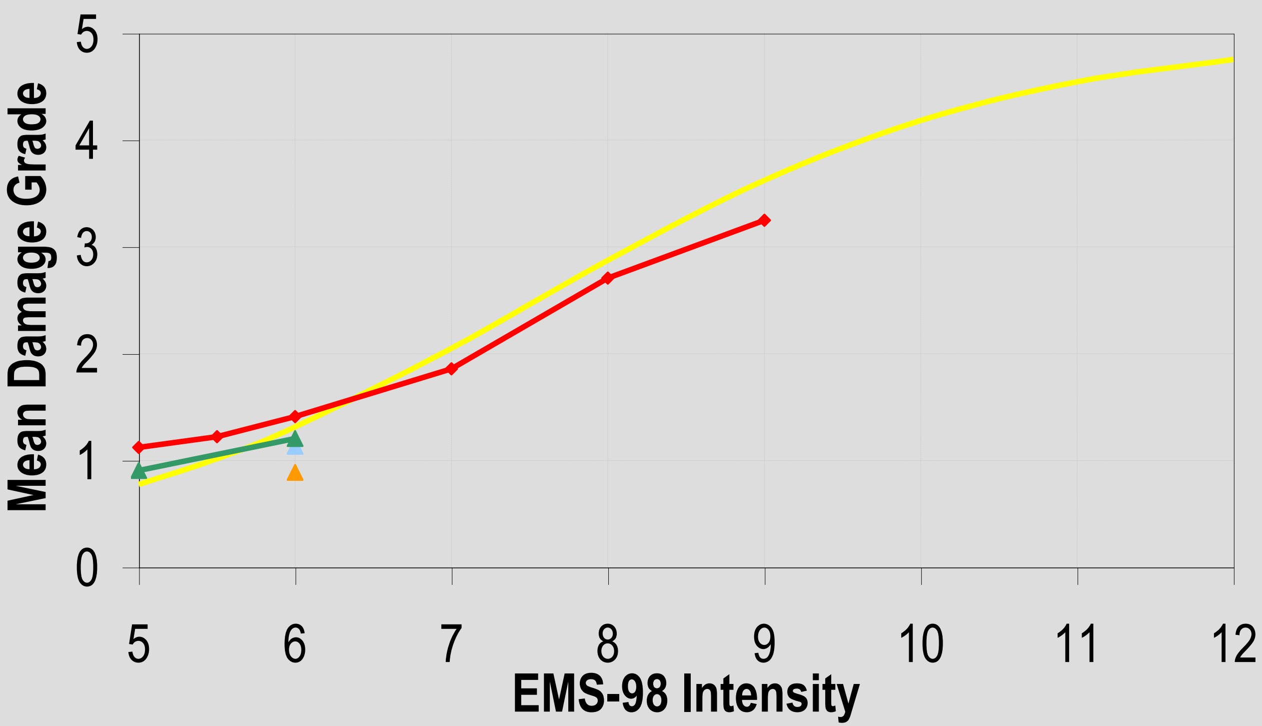


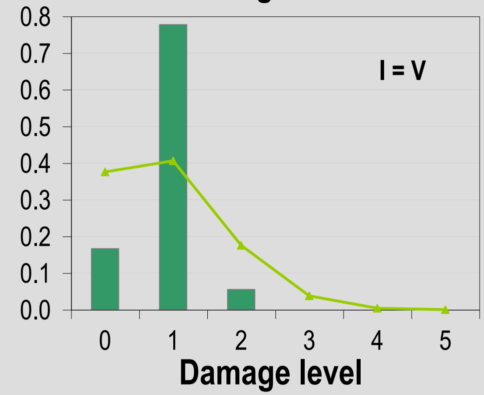
Validation by observed data





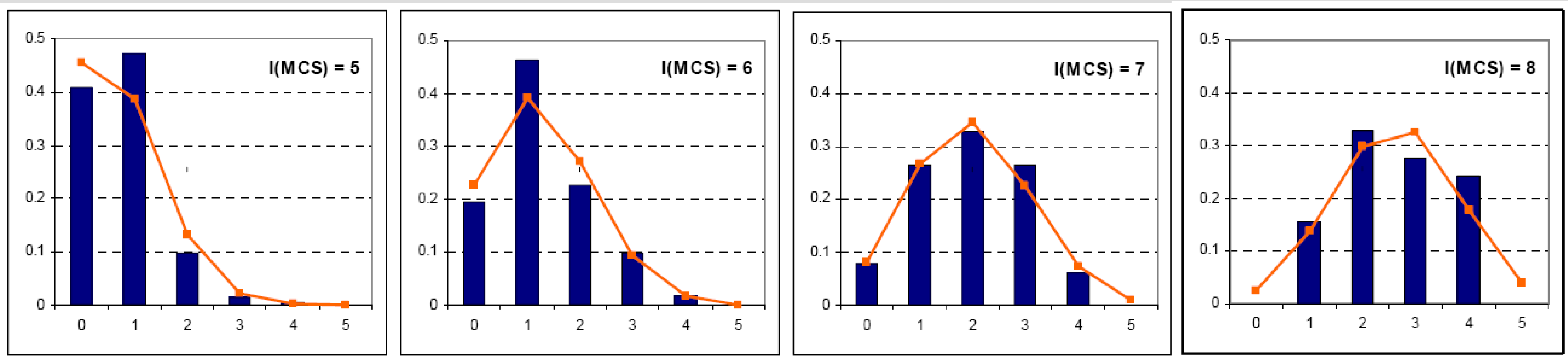




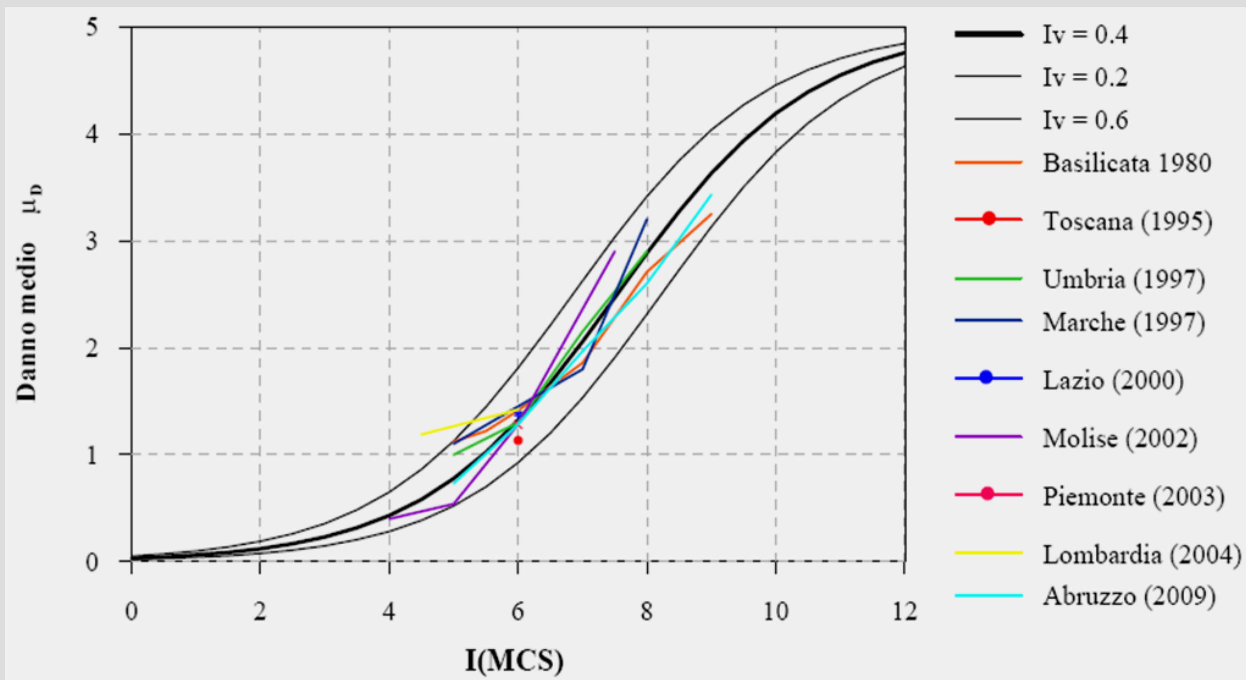


DAMAGE ASSESSMENT TO CHURCHES AFTER L'AQUILA EARTHQUAKE

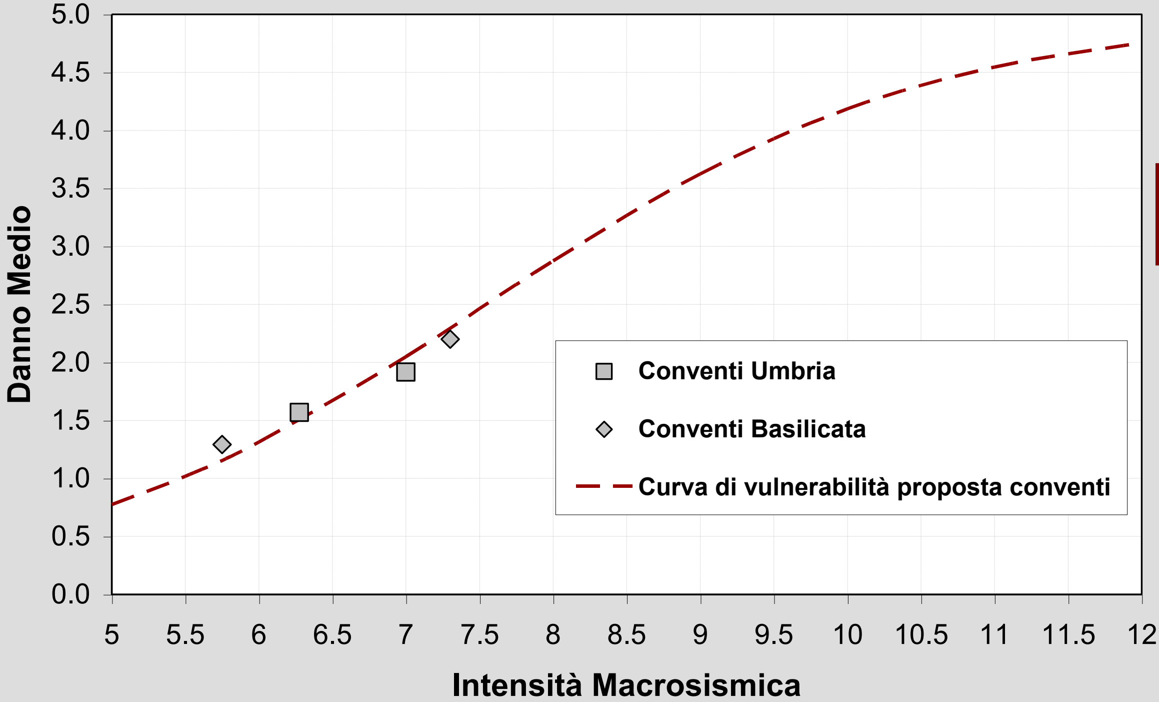
Damage Probability Matrices (DPM) – 654 churches surveyed



Vulnerability curves



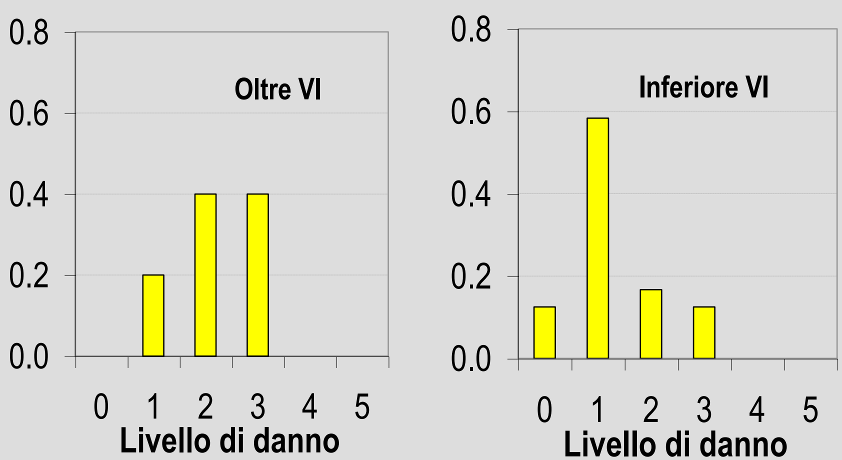
CONVENT - MONASTERY



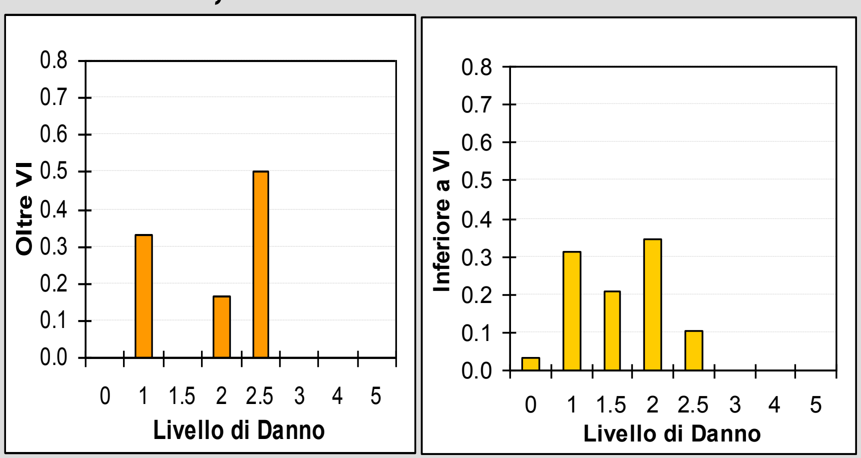
Q = 3	V = 0.89

The vulnerability is, more or less, the same as for churches

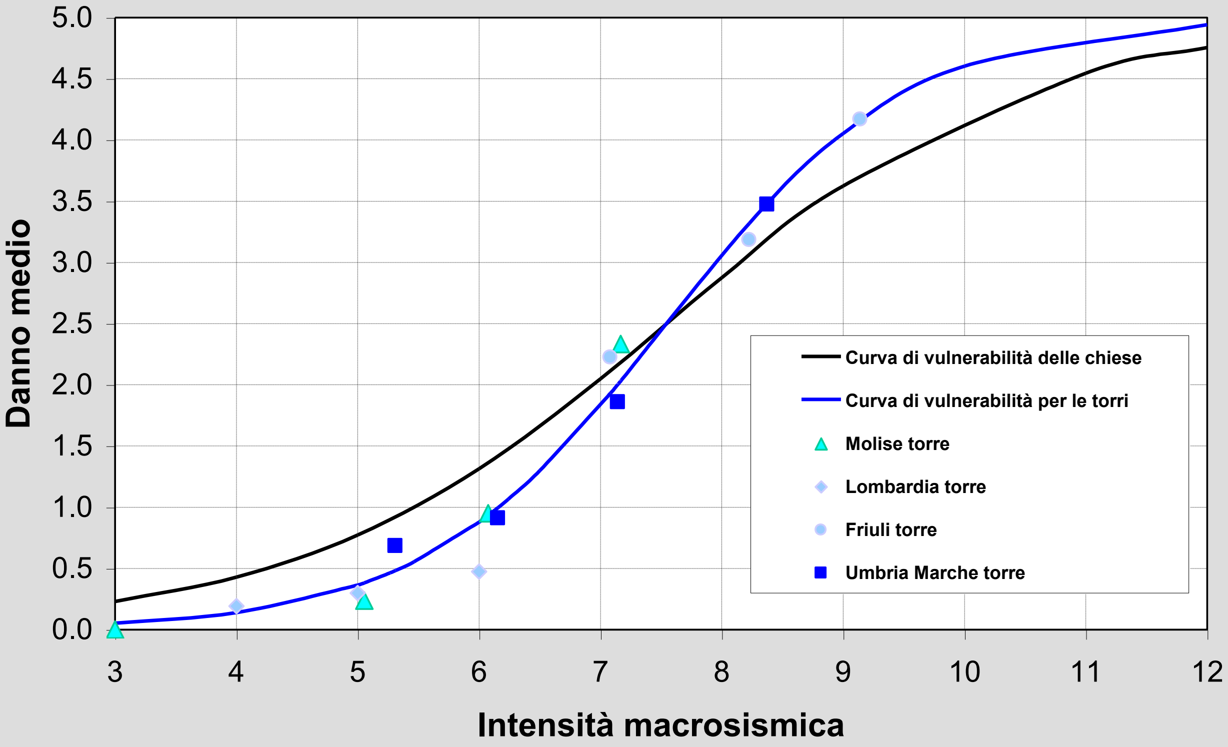
Irpinia, 1980



Umbria, 1997



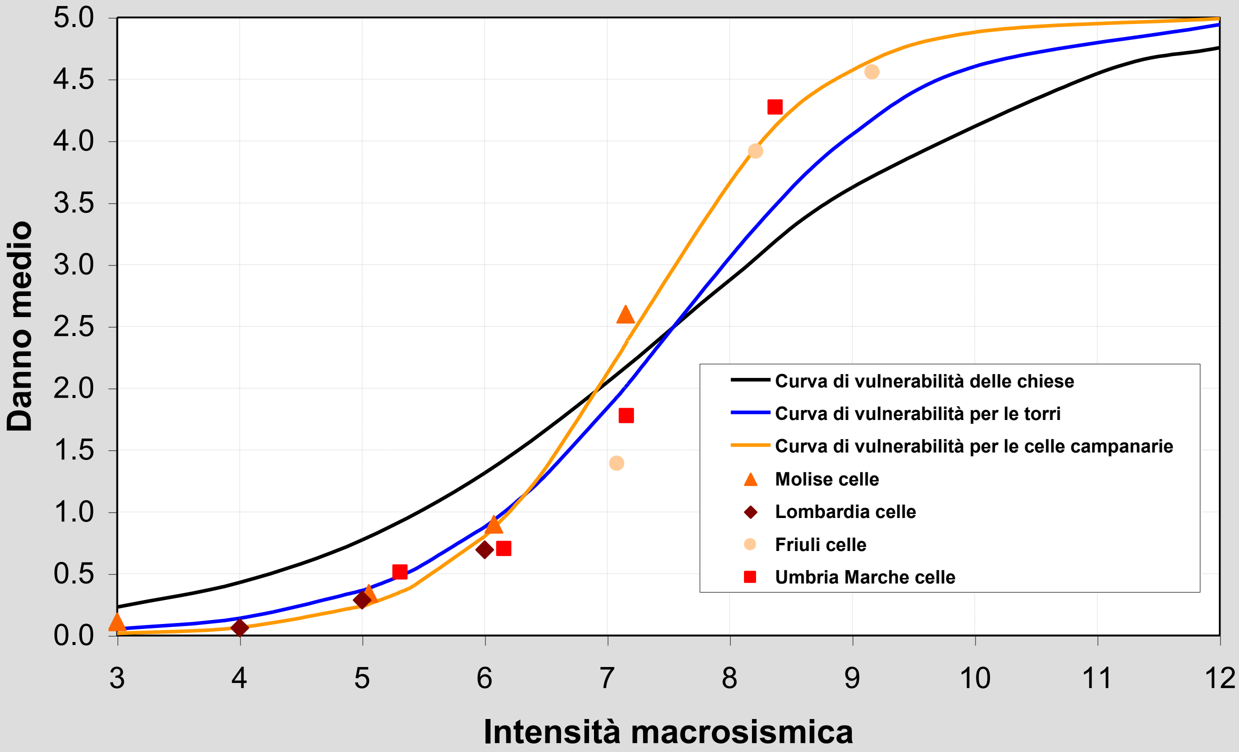
TOWER



Q = 2	V = 0.89

Vulnerability is lower than churches for low intensity earthquakes, but it is higher with the increase of intensity (low ductility index Q)

BELFRY



Q = 1.49	V = 0.94

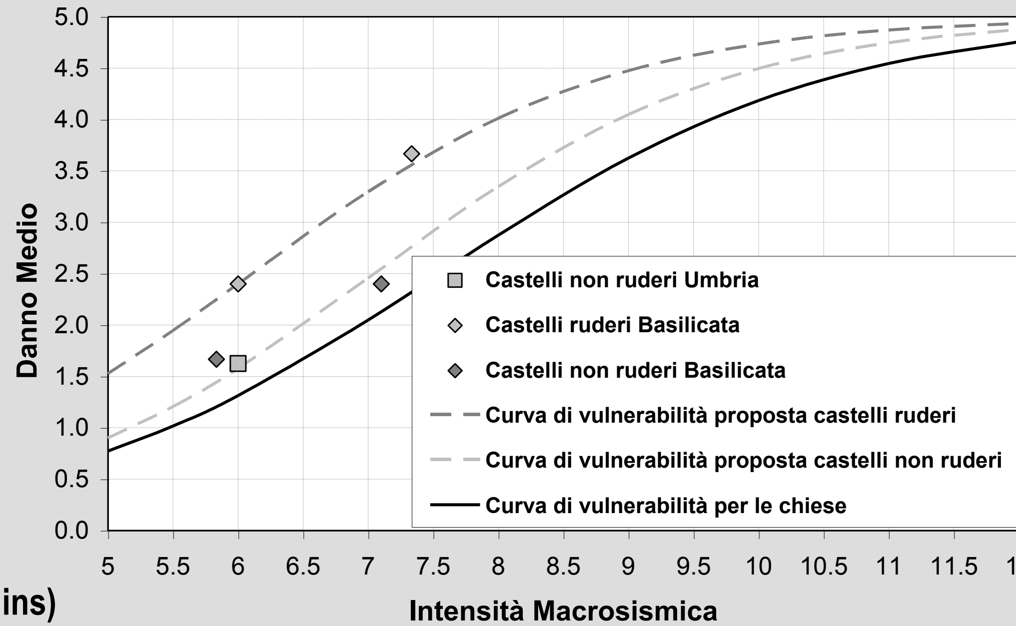
- Lower displacement capacity of the piers in the belfry, with respect to the global tower
- Amplification of the motion at the base of the belfry

CASTLE

Q = 2.7	V = 0.97

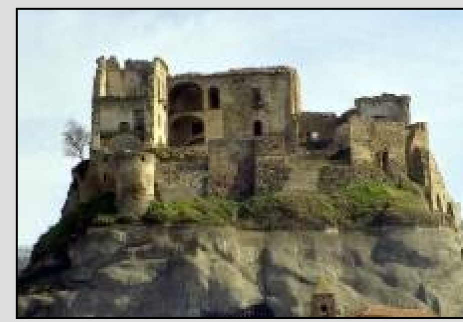
Vulnerability score modifier

$\Delta V_I = 0.2$



Bad state of maintenance before the earthquake (ruins)

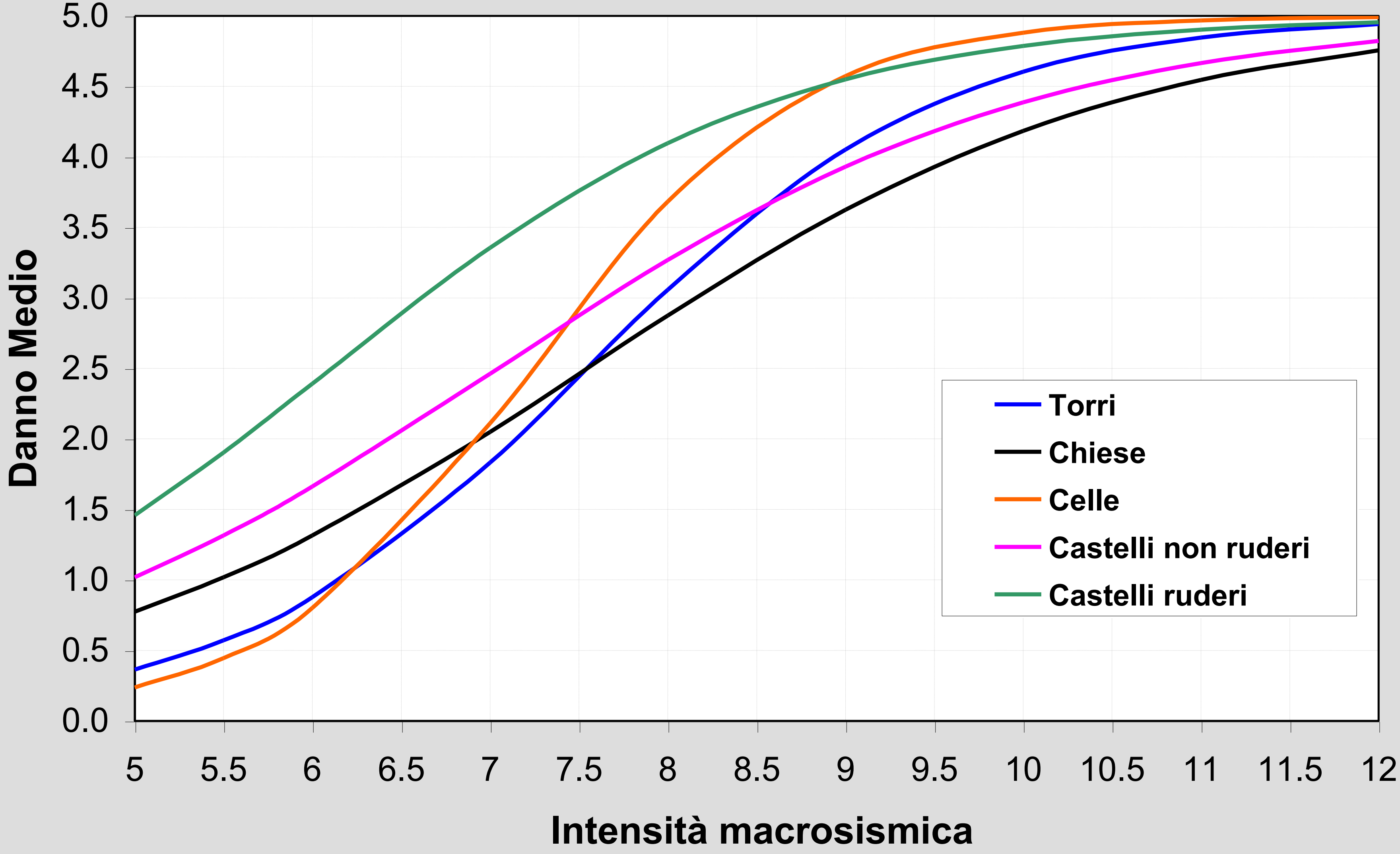




Good state of maintenance before the earthquake



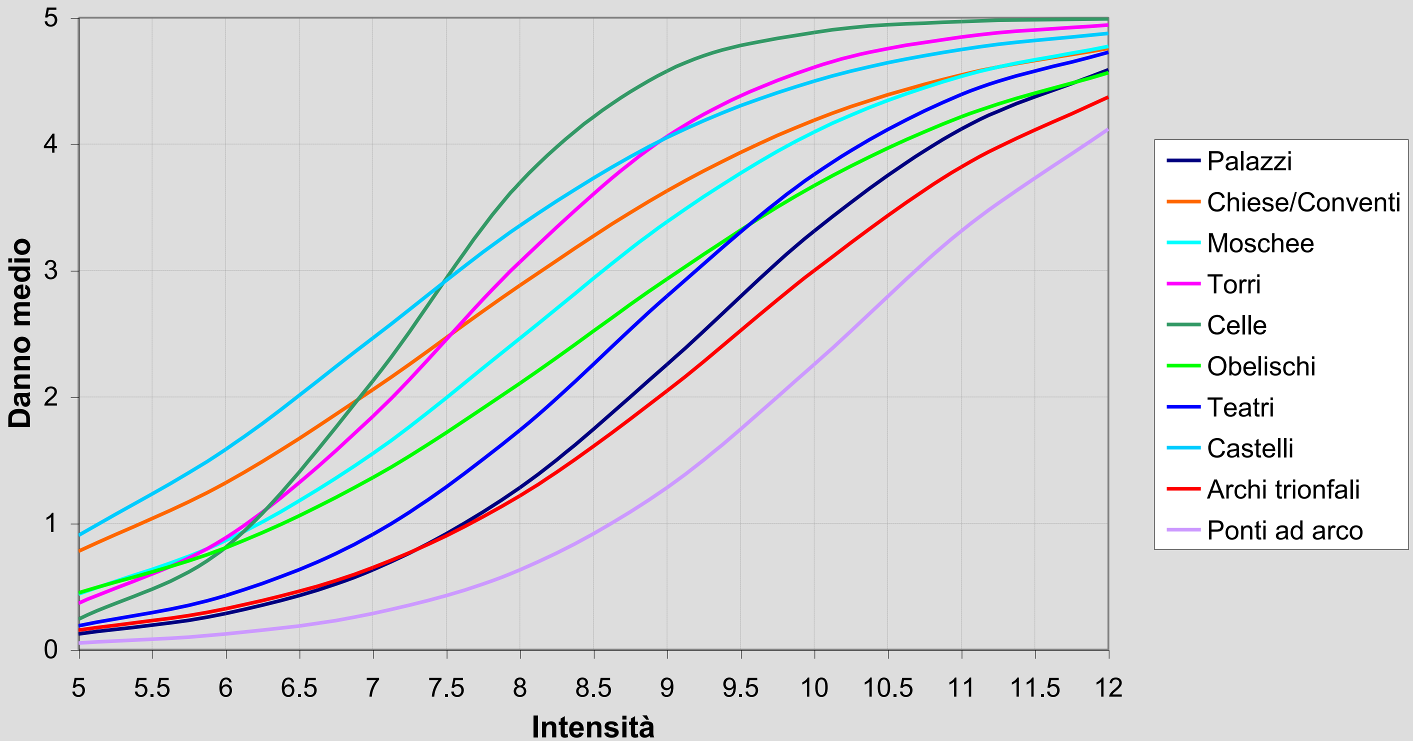
Macroseismic method



Macroseismic method – RISKUE Project

TYPE	V_0	Q
Palace	0.62	2.3
Church	0.89	3.0
Convent	0.89	3.0
Tower	0.89	2.0
Belfry	0.94	1.49

TYPE	V_0	Q
Obelisk	0.74	3
Theatre	0.70	2.3
Castel	0.97	2.7
Triumphal arch	0.58	2.6
Arch bridge	0.46	2.3



Macroseismic method - Level 1

Vulnerability survey and damage scenario of monuments in Catania (Sicily)

150 monumental buildings have been surveyed in the city, with a quick vulnerability form that needs poor data (typology and some easily noticeable parameters as state of maintenance, material quality, regularity in plan and in elevation, etc.).

The mean value of the vulnerability index V is modified by:

- **general parameters**

State of preservation	worst	+ 0.04
	medium	0
	good	- 0.04
Damage level	severe	+ 0.04
	light	+ 0.02
	none	0
Architectural transformations	yes	+ 0.02
	no	0
Recent interventions	yes	+ 0.02
	no	- 0.02

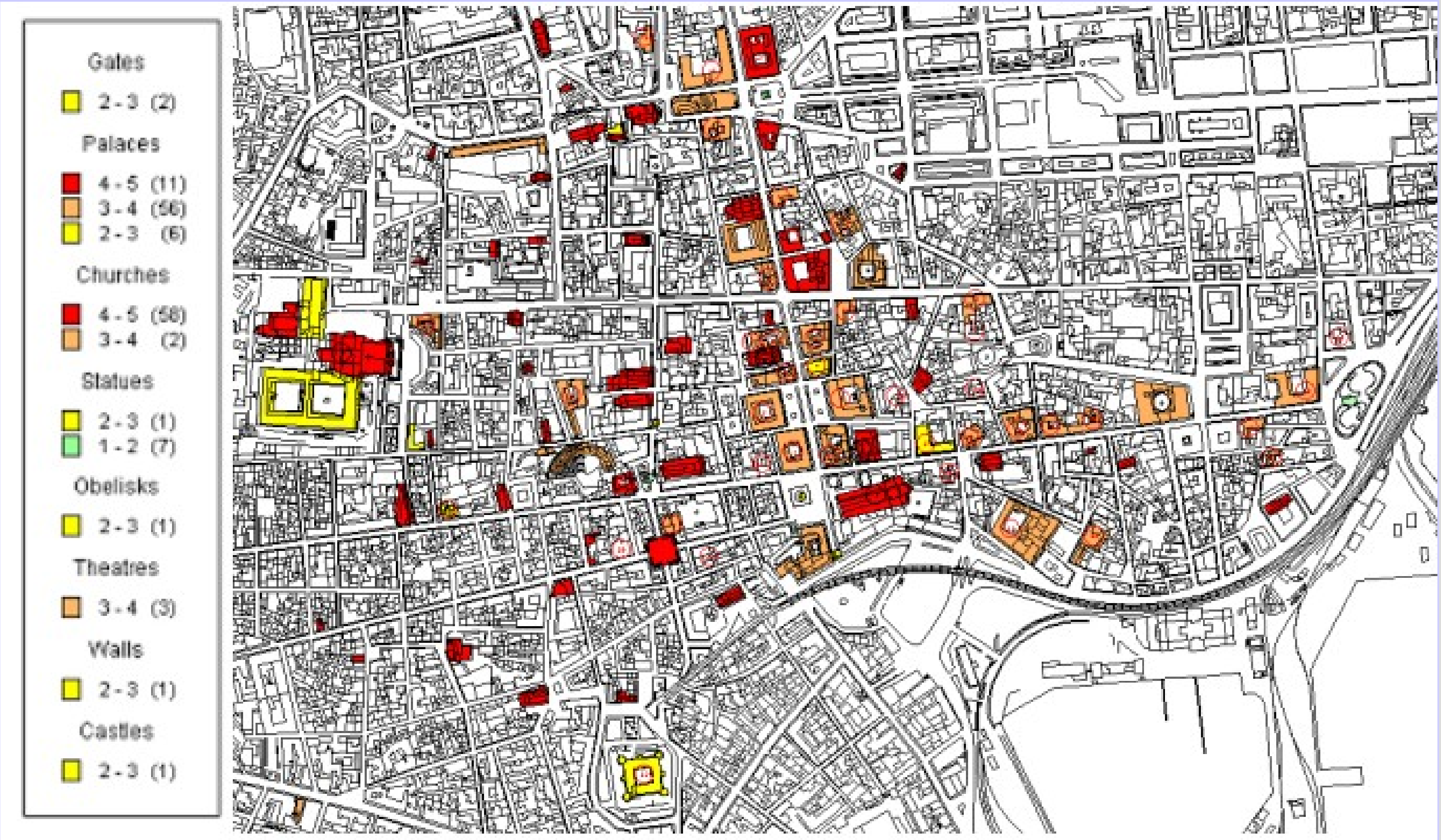
Masonry quality	yes	+ 0.05
	no	0
Site morphology	ridge	+ 0.04
	sloping	+ 0.02
	flat ground	0
Plan regularity	*It depends from the typology*	
Section regularity	*It depends from the typology*	
Position	*It depends from the typology*	

- **specific parameters, depending on the typology**

Macroseismic method - Level 1

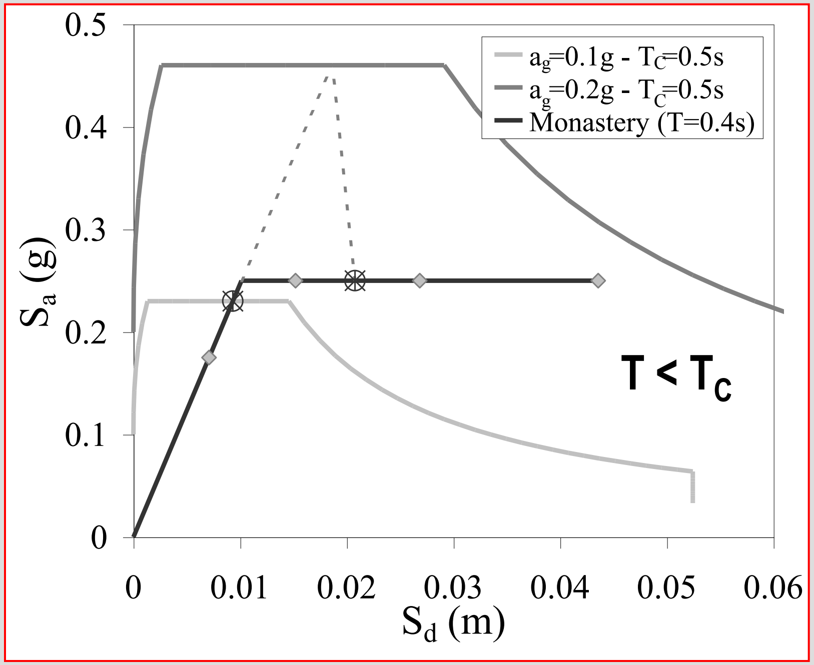
EXAMPLE OF APPLICATION

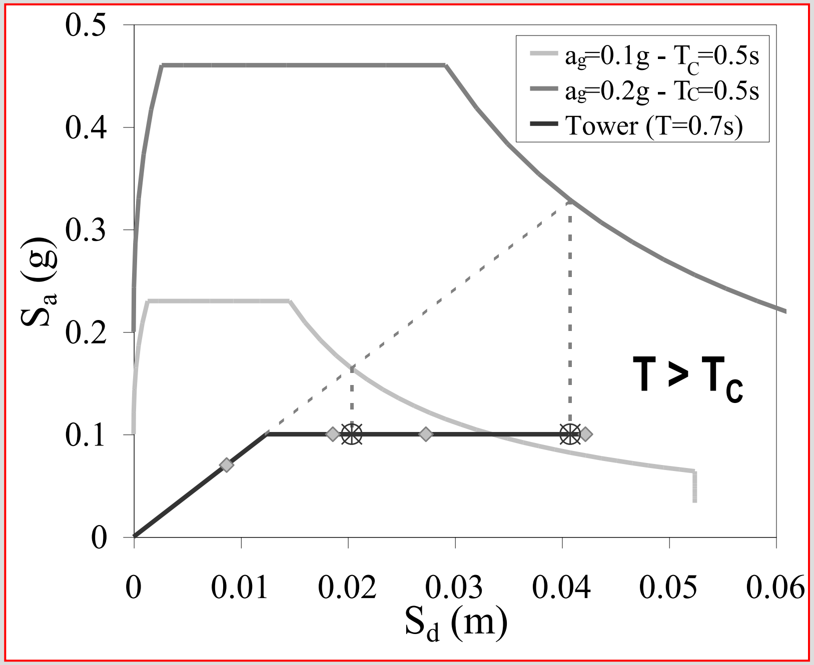
Damage scenarios in Catania (Sicily): replication of 1693 earthquake (mean damage grade μ_D)



MECHANICAL VULNERABILITY MODELS

Capacity Spectrum Method: comparison between the DEMAND of the earthquake and the CAPACITY of the structure (1 d.o.f. non-linear system)





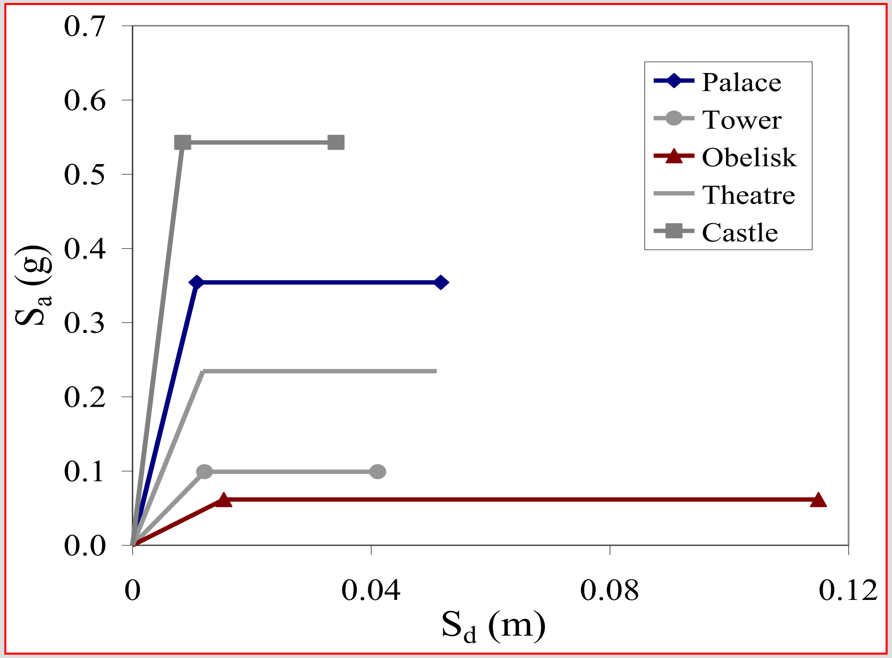
$$S_{d*} = \begin{cases} [1+(q-1)T_C/T]d_y & T < T_C \text{ and } q > 1 \\ q d_y & T_C \le T < T_D \text{ or } q \le 1 \\ S_{ae}(T_D)T_D^2/4\pi^2 & T \ge T_D \end{cases}$$

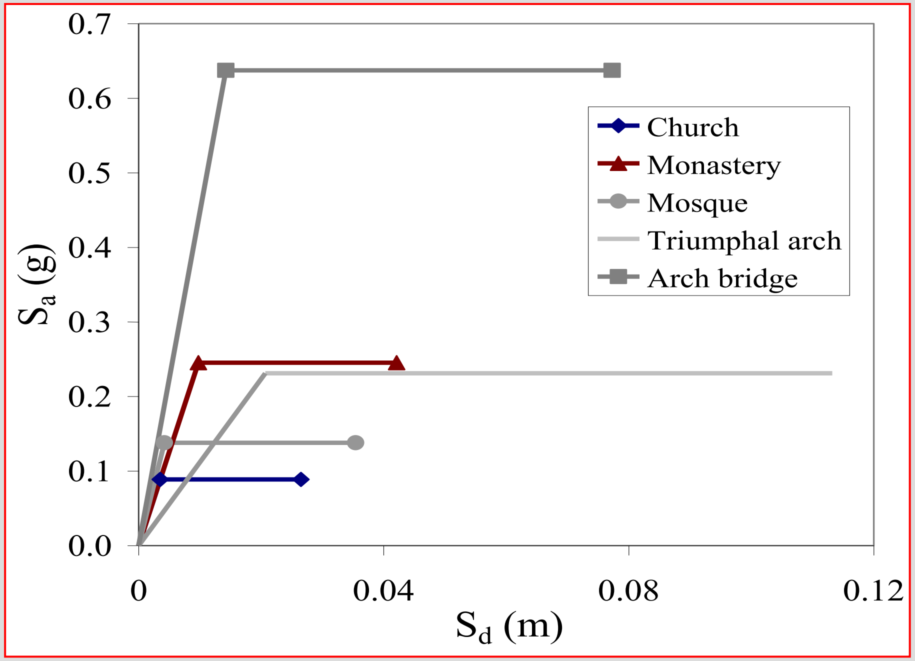
Mechanical method

The capacity curve is defined by 3 parameters:
a) the fundamental period (T), b) the yelding spectral acceleration (a_y), c) the ductility (μ).

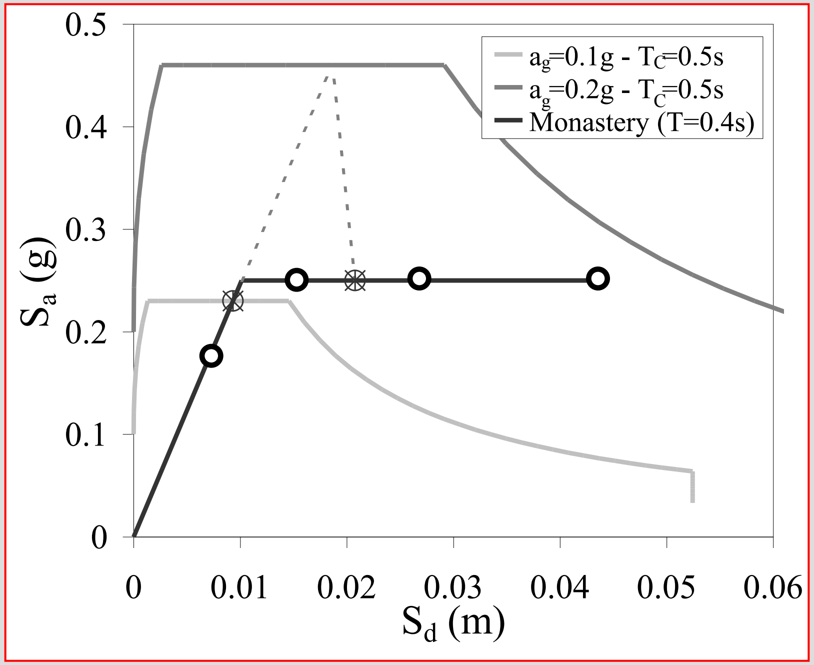
Simple mechanical models can be used to evaluate the capacity curve of a masonry structure.

Capacity curves can also be obtained, for each monumental type, by an equivalence with the macroseismic model.





Mechanical method

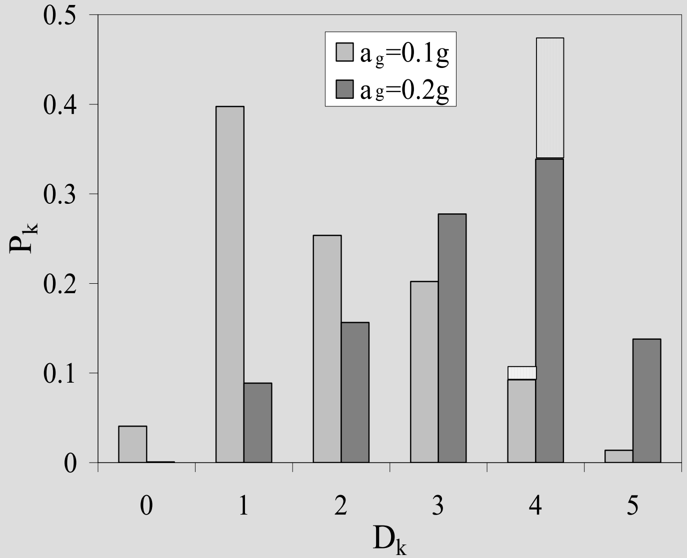


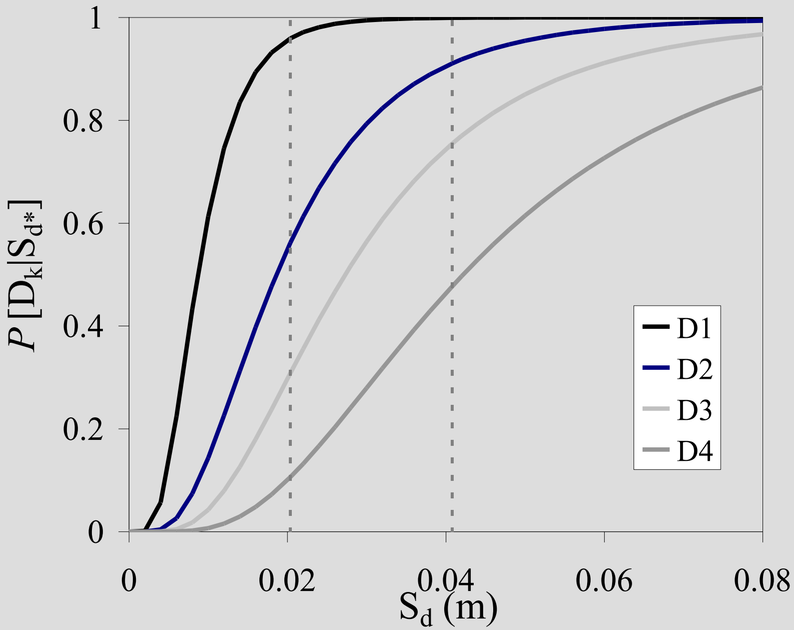
Damage limit states

D_k	$S_{d,k}$
1	0.7 d_y
2	1.5 d_y
3	0.5 (1+μ) d_y
4	μ d_y

Fragility curves

$$P\left[D_k \middle| S_{d*}\right] = \Phi\left[\frac{1}{\beta_k}\ln\left(\frac{S_{d*}}{S_{d,k}}\right)\right]$$





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

LV1 - Vulnerability assessment of monuments at territorial scale Analisys by simplified mechanical or statistically based models

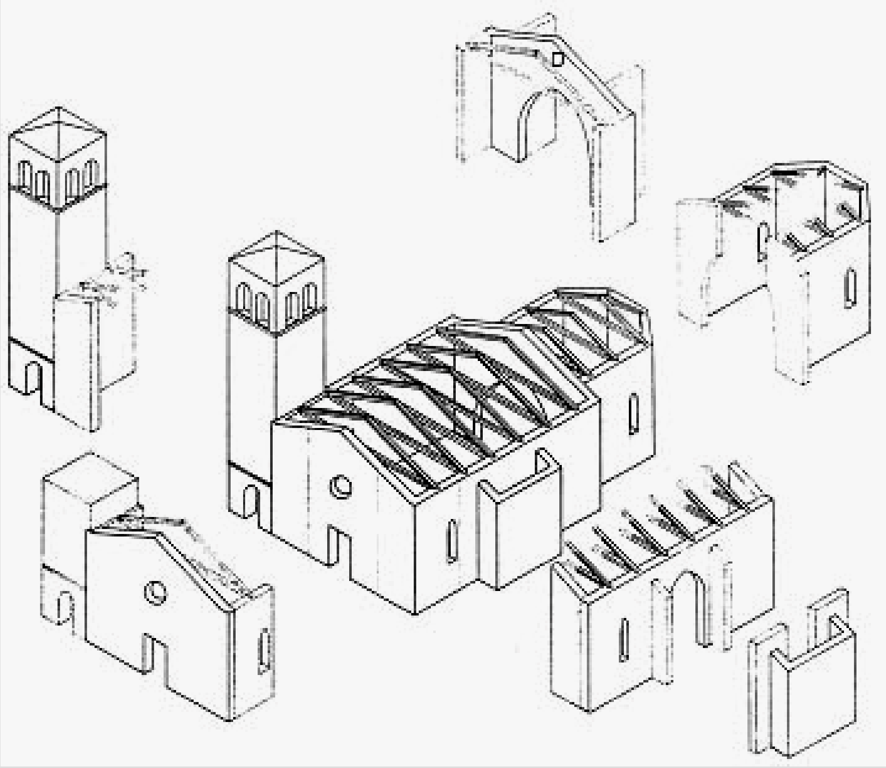
CHURCHES
PALACES
TOWERS

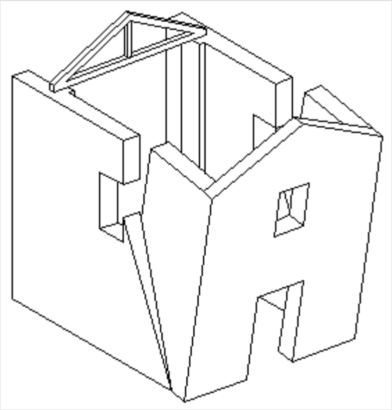
volumi pubblicati da
GANGEMI EDITORE

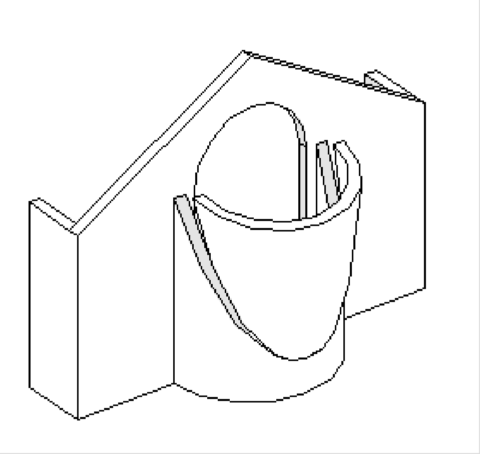
Vulnerability model for CHURCHES

The methodology is based on the identification of macroelements, which consist of architectonic elements whose seismic behavior may be assumed as almost independent from the rest of the structure, and of their possible collapse mechanisms (in all 28).

19 – MECCANISMI NEGLI ELEMENTI DI COPERTURA - PARETI LATERALI DELL'AULA				
Presenza del macroelemento in relazione al meccanismo: Si ☐ No ☐				Punta di danno massimo (da 0 a 5): __
Vulnerabilità	Si	No	*Presidi antisismici*	
	☐	☐	Presenza di cordoli leggeri (metallici reticolari, muratura armata, c.a. sottili)	☐☐☐
	☐	☐	Presenza di collegamento puntuale delle travi alla muratura	☐☐☐
	☐	☐	Presenza di controventi di falda (tavolato incrociato o tiranti metallici)	☐☐☐
	☐	☐	Presenza di buone connessioni tra gli elementi di orditura della copertura	☐☐☐
	☐	☐	… …	☐☐☐
	Si	No	*Indicatori di vulnerabilità*	
	☐	☐	Presenza di copertura staticamente spingente	☐☐☐
	☐	☐	Presenza di cordoli rigidi, copertura pesante	☐☐☐
	☐	☐	… …	☐☐☐
Danno	attuale		Lesioni vicine alle teste delle travi lignee, scorrimento delle stesse – Sconnessioni tra i cordoli e muratura – Movimenti significativi del manto – Sconnessioni e movimenti tra gli elementi di orditura principale	☐☐☐☐☐
	vecchio		Lesioni vicine alle teste delle travi lignee, scorrimento delle stesse – Sconnessioni tra i cordoli e muratura – Movimenti significativi del manto – Sconnessioni e movimenti tra gli elementi di orditura principale	☐☐☐☐☐







Vulnerability model for CHURCHES

The methodology is based on the identification of macroelements, which consist of architectonic elements whose seismic behavior may be assumed as almost independent from the rest of the structure, and of their possible collapse mechanisms (in all 28).

Damage index

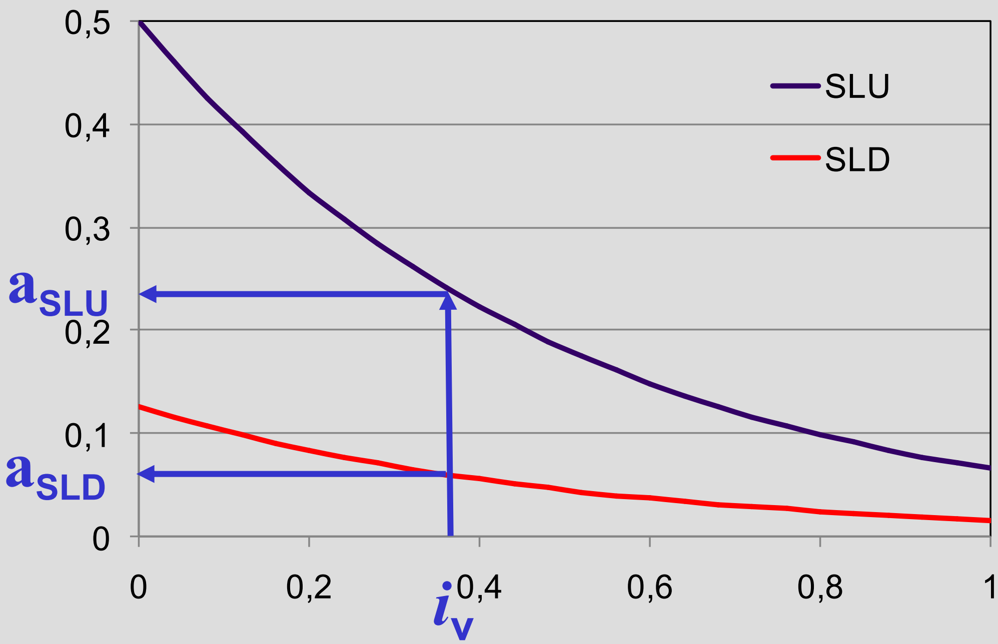
$$i_d = \frac{1}{5} \frac{\sum_{k=1}^{n} \rho_k d_k}{\sum_{k=1}^{n} \rho_k}$$

Vulnerability index

$$i_v = \frac{1}{6} \frac{\sum_{k=1}^{n} v_{ki} - v_{kp}}{\sum_{k=1}^{n} \rho_k} + \frac{1}{2}$$

$$a_{SLU} = 0.025 \cdot 1.8^{5.1 - 3.44 i_v}$$

$$a_{SLD} = 0.025 \cdot 1.8^{2.75 - 3.44 i_v}$$



Vulnerability model for TOWERS

procedure proposed in the Italian Guidelines for evaluation and mitigation of seismic risk to cultural heritage (Directive of the Prime Minister, 12/10/2007).

Chiesa di S.Maria Assunta (Gemona)

S.Pietro e Paolo (Maiano)

Chiesa di S.Stefano (Cavazzo Carnico)

Vulnerability model for TOWERS

The model is based on the flexural failure of the tower, at different possible sections, due to axial (gravity loads) and bending (due to seismic equivalent horizontal actions).

Capacity

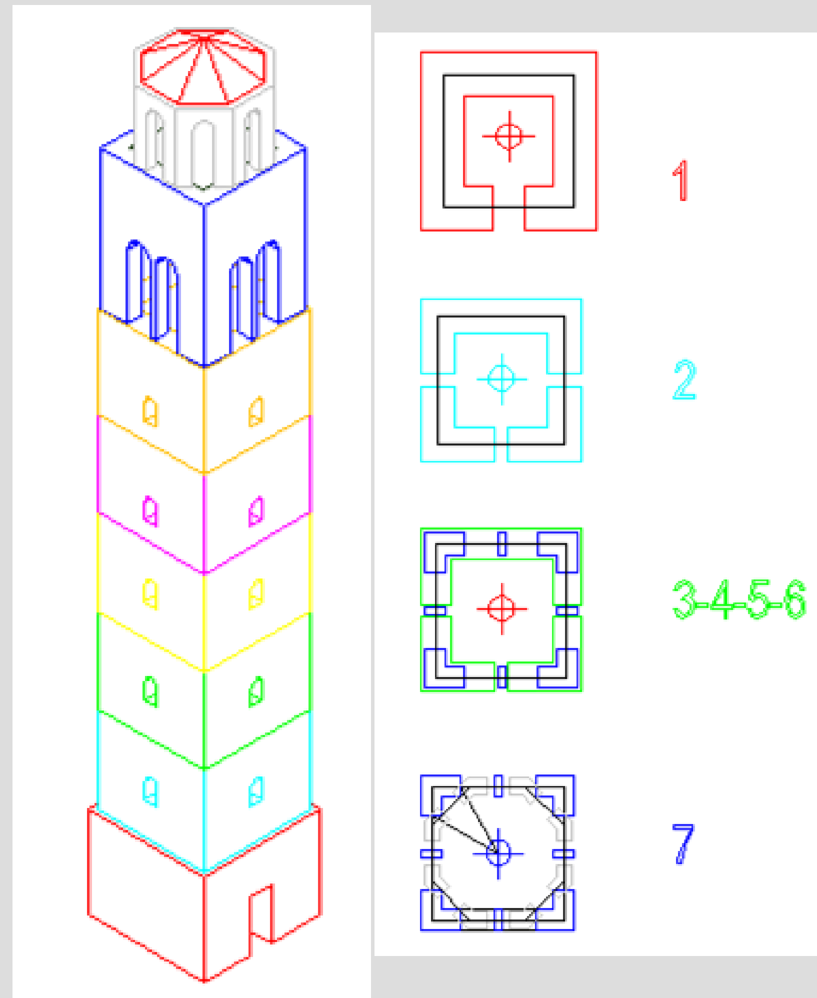
$$M_{u,i} = \frac{\sigma_{0i} A_i}{2}\left(b_i - \frac{\sigma_{0i} A_i}{0.85 a_i f_d}\right)$$

Demand

$$F_i = \frac{W_i z_i}{\sum_{k=1}^{n} W_k z_k} F_h \qquad F_h = 0.85 S_e(T_1) W / qg$$

$$S_{e,SLV,i}(T_1) = \frac{q\, g\, M_{u,i} \sum_{k=1}^{n} z_k W_k}{0.85 W \left(\sum_{k=i}^{n} z_k^2 W_k - z_{i*} \sum_{k=i}^{n} z_k W_k \right) F_C}$$

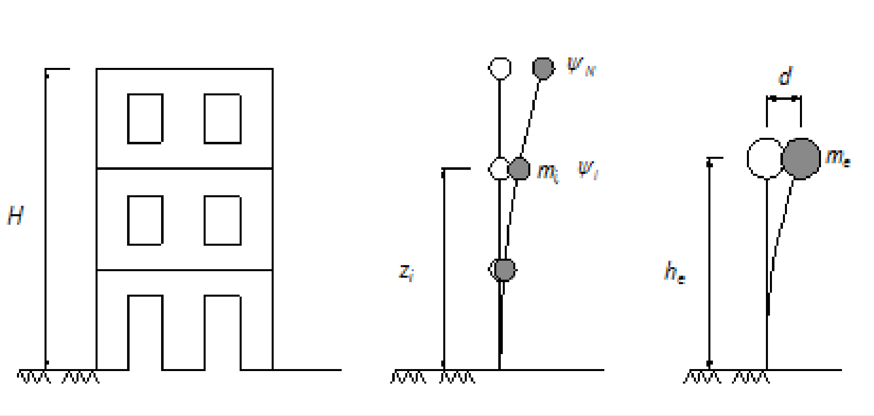
$$a_{SLV} = \begin{cases} \dfrac{S_{e,SLV}}{SF_0} & T_B \le T_1 < T_C \\ \dfrac{S_{e,SLV}}{SF_0} \dfrac{T_1}{T_C} & T_C \le T_1 < T_D \end{cases}$$

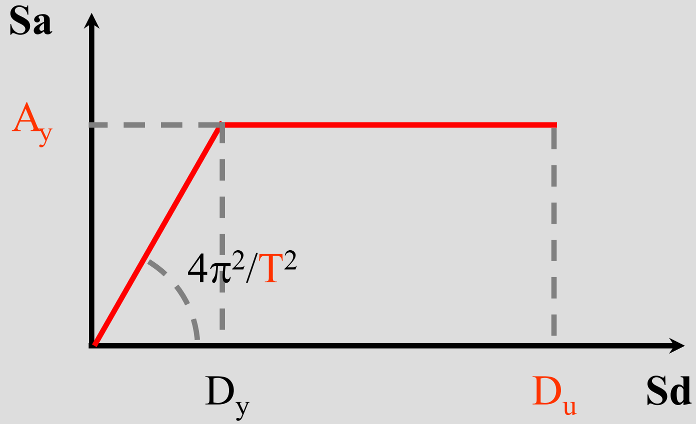


Vulnerability model for PALACES

In order to define a capacity curve by a simplified mechanical model, three parameters are needed:

T (fundamental period) - A_y (yield acceleration) - D_u (collapse displacement)





Evaluation of the fundamental period

$$T = 0.05H^{0.75}$$

(H – height of the building)

Vulnerability model for PALACES

Evaluation of the collapse displacement (weak storey mechanism)

$$D_u = \delta_u \, h + D_y \left(1 - \frac{\Gamma}{N} \right)$$

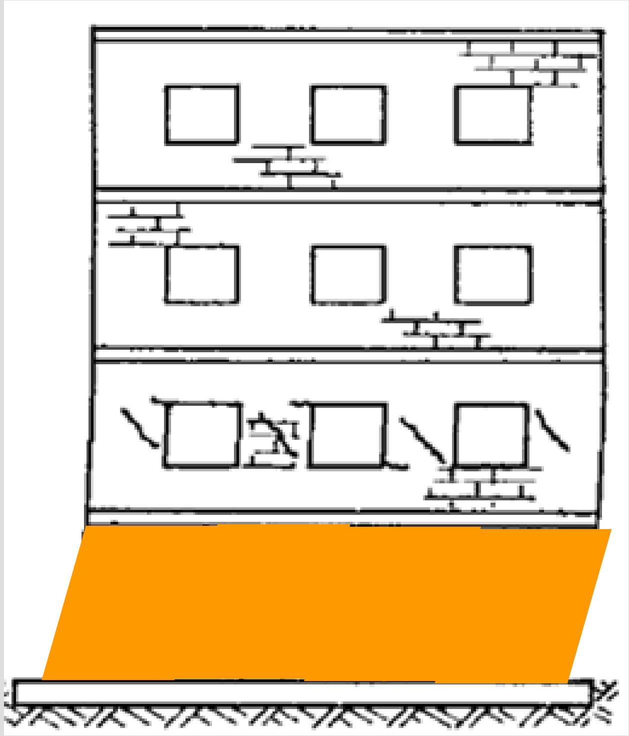
δ_u is the ultimate drift of the masonry panels (in the Italian seismic code:

- 0.4% in the case of shear collapse
- 0.6% in the case of rocking (axial-bending)

h is the inter-storey height

$$\Gamma = \frac{\left(\sum_{k=1}^{N} \phi_k \right)^2}{N \sum_{k=1}^{N} \phi_k^2} = \frac{\lambda}{\sum_{k=1}^{N} \phi_k}$$

$$D_y = \left(\frac{T_y}{2\pi} \right)^2 A_y$$



Vulnerability model for PALACES

Evaluation of the yield acceleration (shear strength)

The model is based on the hypothesis that all masonry panels of a generic storey k reach the maximum shear strength at the same time (for the same displacement).

$$A_{y,x,k} = \frac{1}{\lambda M} F_{SLU,x,k} = \frac{\alpha_k}{\lambda M} \frac{\sum_{i=1}^{M_{x,k}} A_{k,i}\tau_{r,k,i}}{\ }$$

Corrective coefficients:

- Variability in slenderness of masonry panels

$$\mu_{x,k} = 1 - 0.2\sqrt{\frac{M_{x,k}\sum_{i=1}^{M_{x,k}} A_{k,i}^2}{\left(\sum_{i=1}^{M_{x,k}} A_{k,i}\right)^2}} \geq 0.8$$

- Plan irregularity (eccentricity)

$$\beta_{x,k} = 1 + 2\frac{e_{yk}}{d_{yk}} \leq 1.2$$

Vulnerability model for PALACES

Evaluation of the yield acceleration (shear strength)

The model is based on the hypothesis that all masonry panels of a generic storey k reach the maximum shear strength at the same time (for the same displacement).

$$A_{y,x,k} = \frac{1}{\lambda M} F_{SLU,x,k} = \frac{\mu_{x,k} \sum_{i=1}^{M_{x,k}} A_{k,i} \tau_{r,k,i}}{\beta_{x,k}}$$

- α_k **is the fraction of horizontal seismic actions at storey k**

$$\alpha_k = \frac{\sum_{n=1}^{N} z_n M_n}{\sum_{n=k}^{N} z_n M_n}$$

- λM **is the participant mass**
  (λ=1 if N=1; λ=0.9 if N=2 and λ=0.85 if N≥3)

Vulnerability model for PALACES

Evaluation of the yield acceleration (shear strength)

The model is based on the hypothesis that all masonry panels of a generic storey k reach the maximum shear strength at the same time (for the same displacement).

$$A_{y,x,k} = \frac{1}{\lambda M} F_{SLU,x,k} = \frac{\alpha_k}{\lambda M} \frac{\mu_{x,k} \sum_{i=1}^{M_{x,k}}}{\beta_{x,k}}$$

- **$A_{k,i}$ are the section area of the $M_{x,k}$ panels at storey k**
- **$\tau_{r,k,i}$ is the shear strength of each panel, being the minimum between**

rocking failure

$$\tau_{pf,k,i} = \frac{\sigma_{0,k,i} b_{k,i}}{h_{k,i}} \left(1 - \frac{\sigma_{0,k,i}}{0.85 f_{m,k}} \right)$$

diagonal shear failure

$$\tau_{pf,k,i} = \frac{1.5 \tau_{0d,k}}{\kappa_{k,i}} \sqrt{1 + \frac{\sigma_{0,k,i}}{1.5 \tau_{0d,k}}}$$

ARDINGHELLI PALACE, L'AQUILA

Ardinghelli Palace

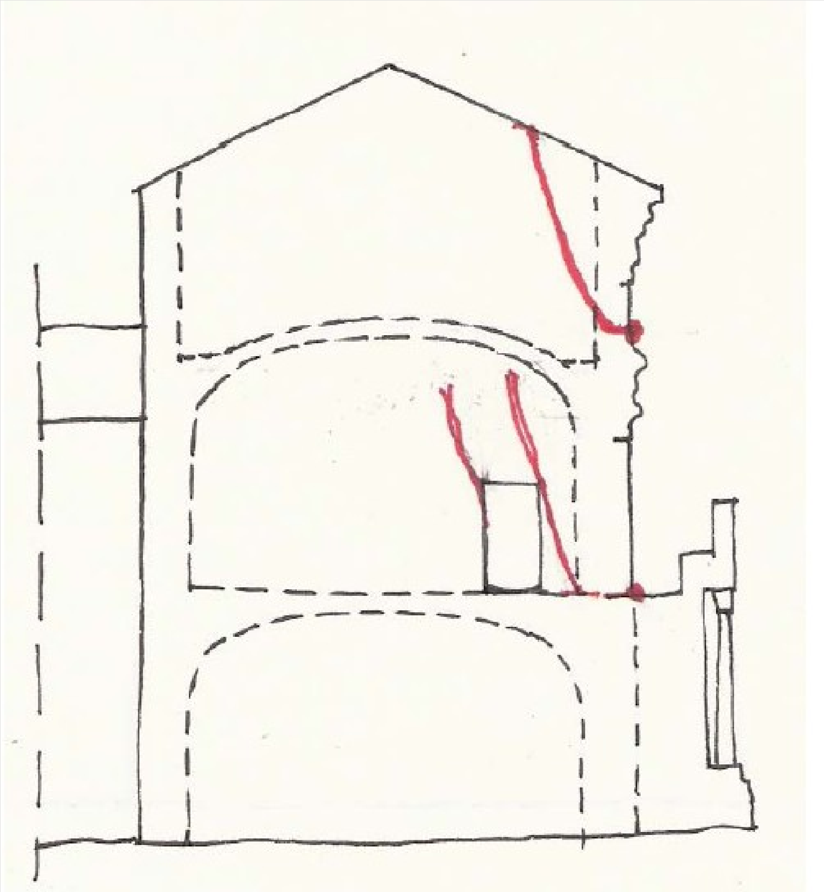
Santa Maria Paganica Church

HISTORICAL NOTES

- Designed after the big earthquake in 1703 (baroque style).
- Composition of existing damaged medieval buildings.
- Exhedra courtyard.
- Very important paintings (frescoes) in the monumental staircase.

PALAZZO ARDINGHELLI – damage mechanisms

Out-of-plane behaviour of the façade

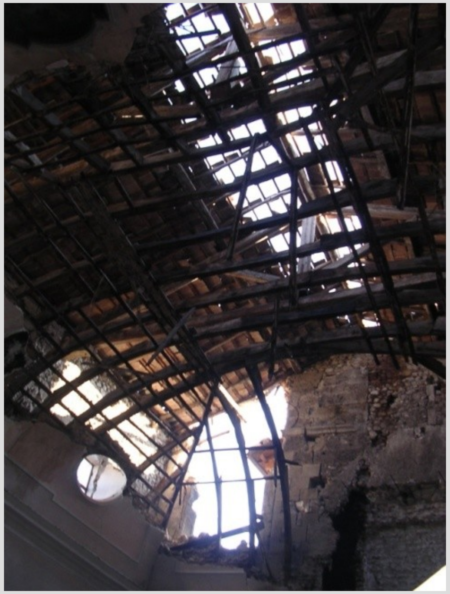


PALAZZO ARDINGHELLI – damage mechanisms

Collapse of brick and light vaults

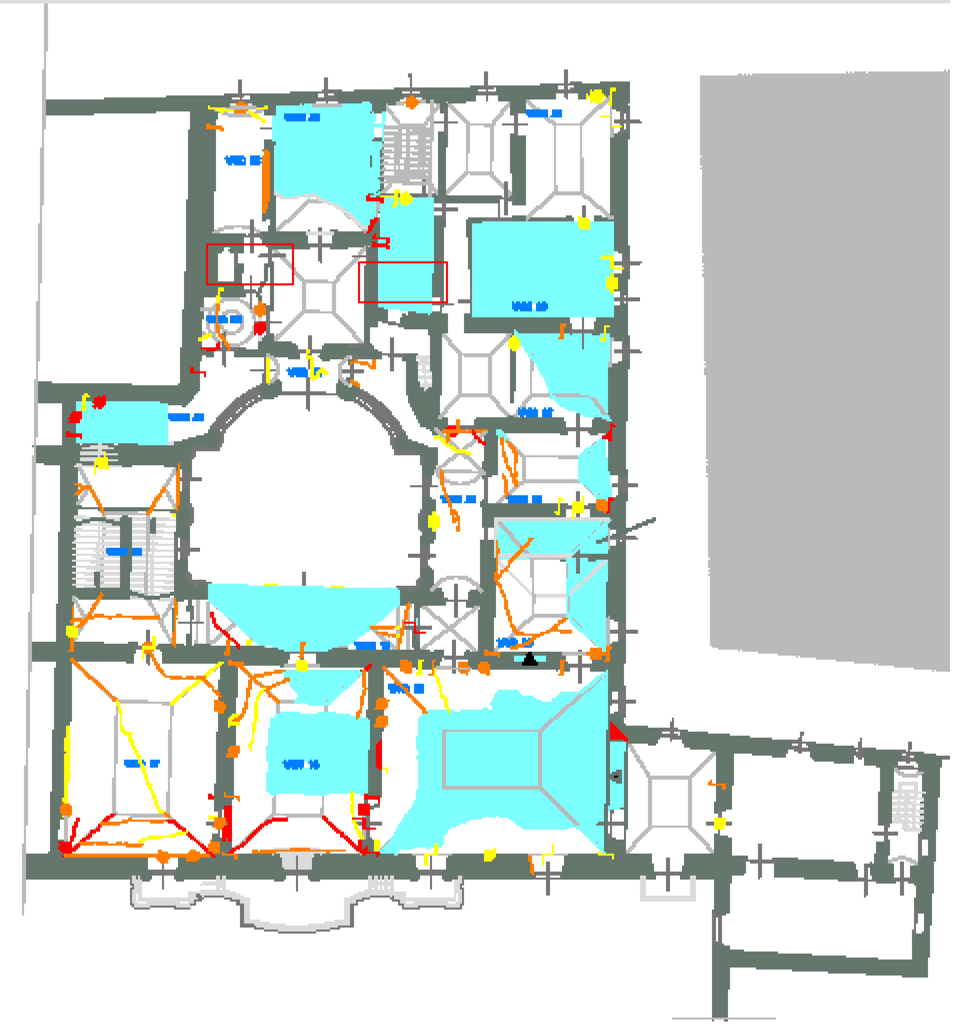




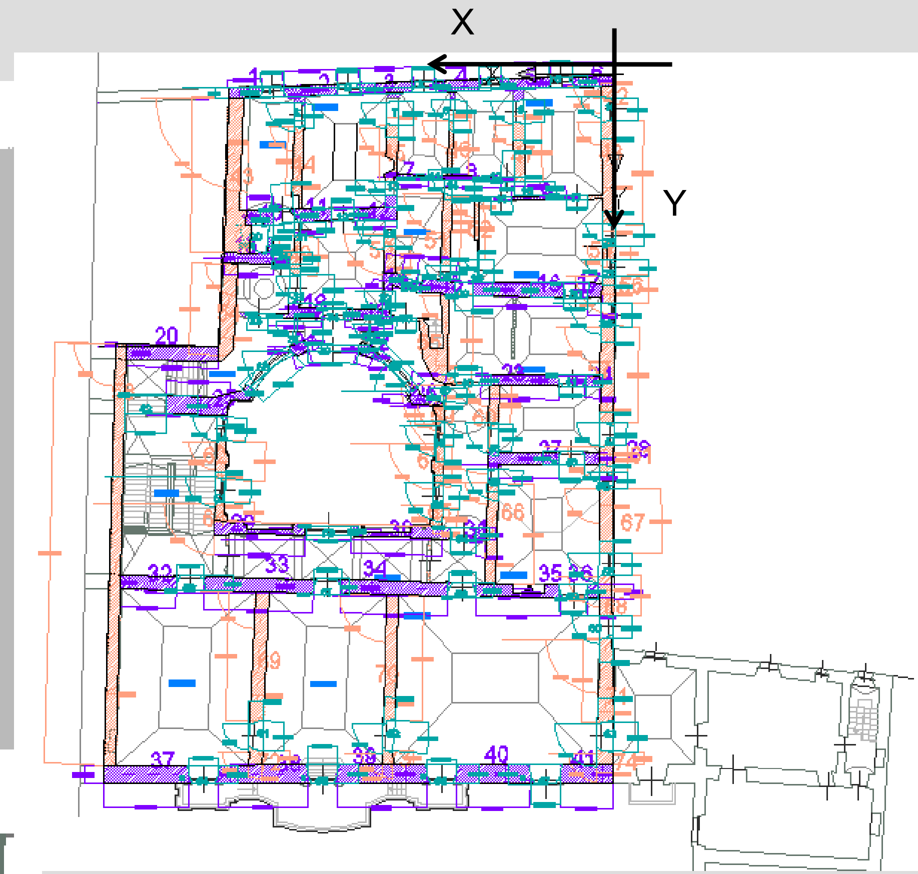


PALAZZO ARDINGHELLI – seismic assessment

Damage in the vaults



Masonry piers in X direction



Peak ground acceleration that produces LIFE SAFETY limit state:

$a_g = 0.28$ g