Field reconnaissance following the April 6, 2009 L`Aquila Earthquake in Italy

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2:30PM

Room 140, Ketter Hall, North Campus, Buffalo NY

Outline

- Seismic ground motion and fault mechanism;
- Italian seismic standard and the role of masonry in seismic zone;
- Damage to historical monuments;
- Damage to critical facilities;
- Damage to industrial buildings;
- Damage to lifelines;
- Damage to RC buildings;

Acknowledgments

- MCEER
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- INGV
- University of Trento (O. Bursi)

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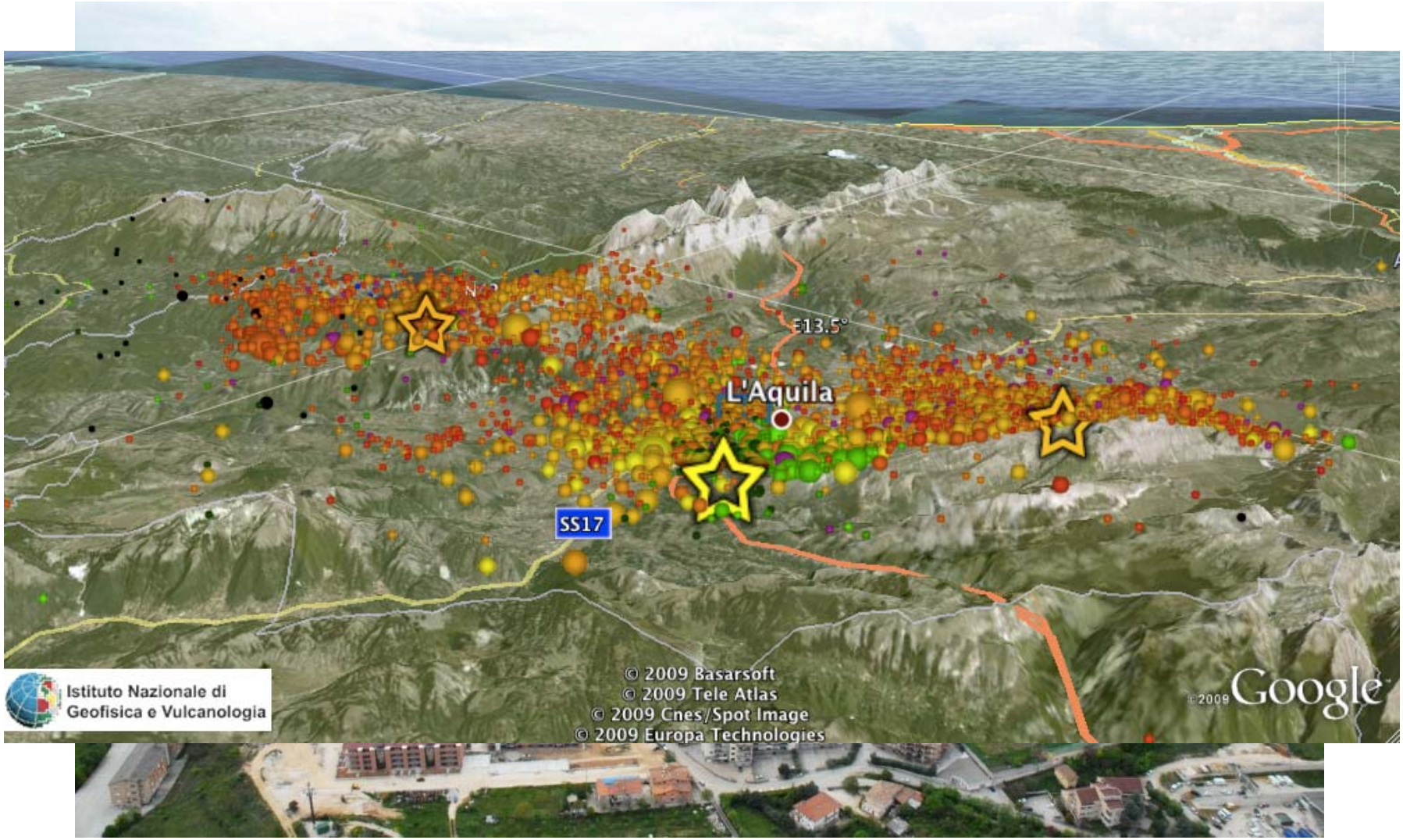
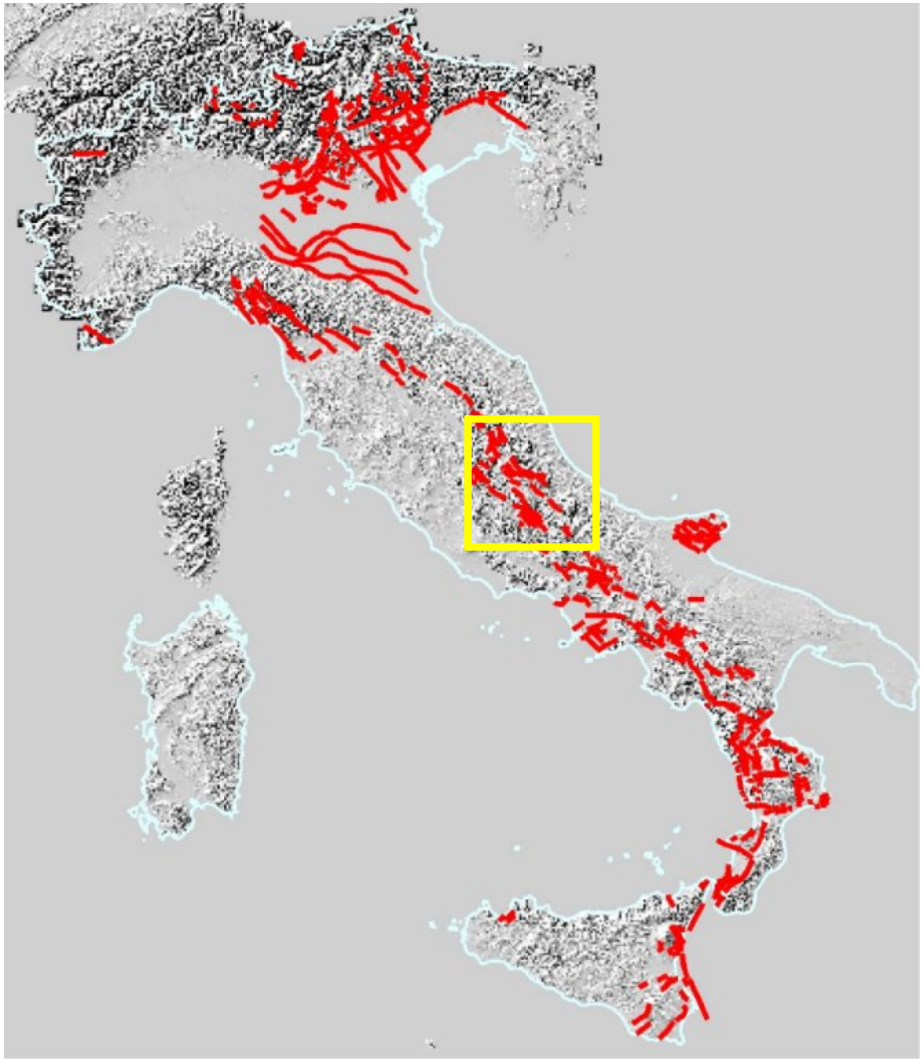
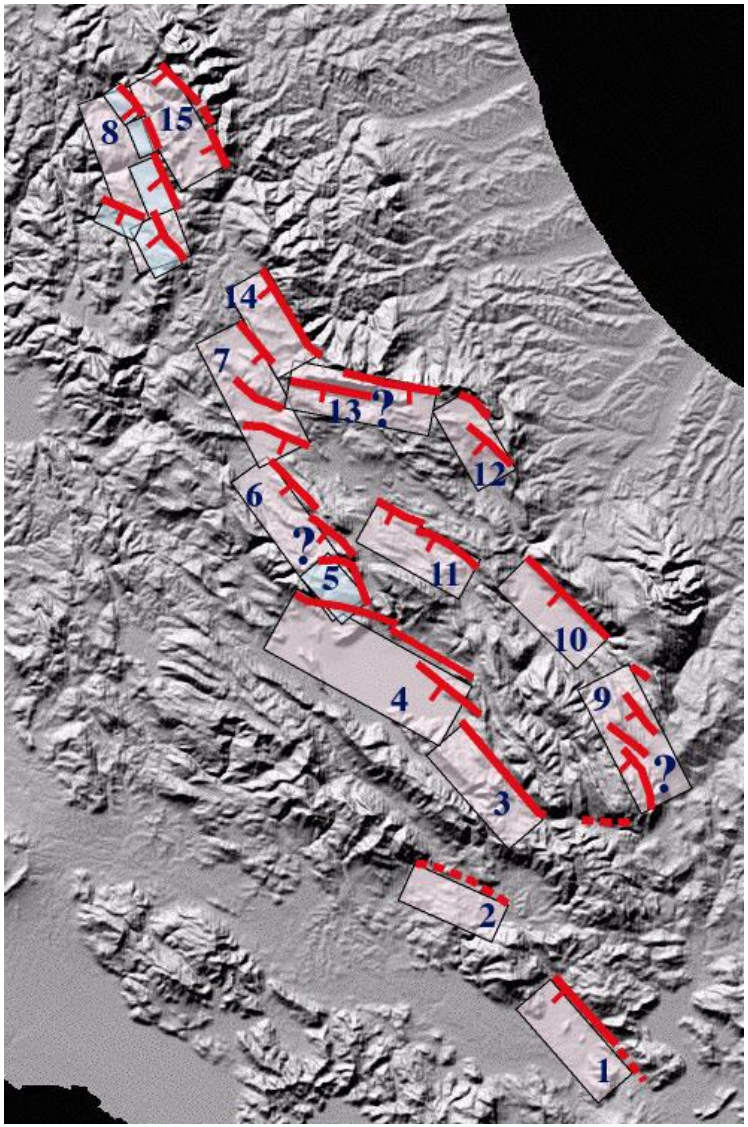
L'Aquila- Areal view



Fault location in Italy





Location of the fault

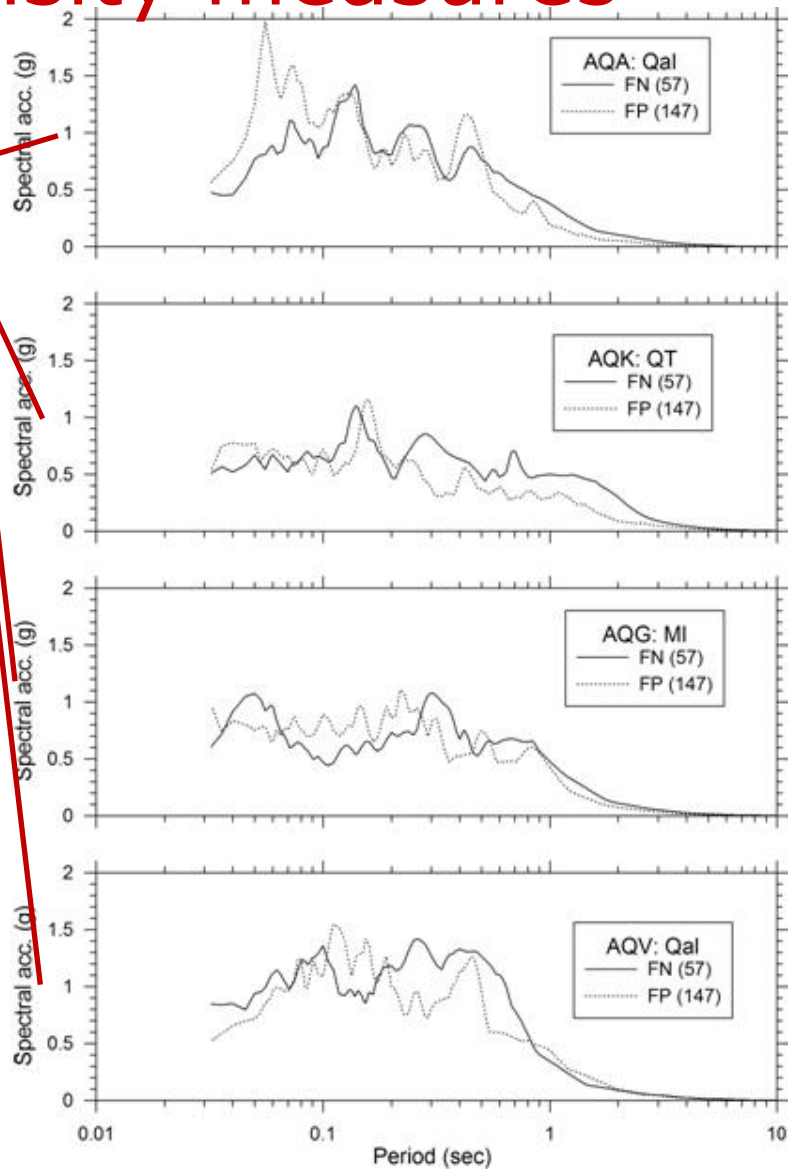
Normal Fault mechanism

Fault surface

- Locations of accelerometers in Abruzzo region;

Ground motion intensity measures

#	Station code	Station Name	R_{epi} (km)	R_{JB} (km)	Azimuth 000 PHA (g)	Azimuth 000 PHV (cm/s)	Azimuth 090 PHA (g)	Azimuth 090 PHV (cm/s)	Vertical PVA (g)	Vertical PVV (cm/s)
1	ANT	ANTRODOCO	23.1	16.2	0.026	2.550	0.020	1.790	0.012	1.170
2	AQA	L'Aquila - V. Aterno -F. Aterno	5.8	0.0	0.443	27.100	0.402	31.900	0.496	9.700
3	AQG	L'Aquila - V. Aterno -Colle Grilli	4.3	0.0	0.515	36.000	0.482	31.100	0.273	10.700
4	AQK	Aquil PARK ing.	5.6	0.0	0.383	36.500	0.341	32.400	0.361	21.600
5	AQV	L'Aquila - V. Aterno - Centro Valle	4.8	0.0	0.554	43.100	0.669	40.400	0.525	12.100
6	ASS	ASSISI	101.7	94.8	0.003	0.393	0.006	0.438	0.002	0.300
7	AVL	AVELLINO	198.1	179.5	0.001	0.418	0.001	0.360	0.001	0.347
8	AVZ	AVEZZANO	34.9	17.5	0.069	11.400	0.056	10.900	0.027	3.750
9	BBN	BIBBIENA	199.6	192.5	0.001	0.256	0.001	0.270	0.001	0.267
10	BDT	BADIA TEDALDA	178.8	171.5	0.002	0.384	0.002	0.293	0.001	0.372
11	BNE	BENEVENTO	180.4	160.7	0.002	0.701	0.002	0.453	0.002	0.415
12	BOJ	BOJANO	133.5	113.7	0.014	3.340	0.013	3.240	0.005	1.440
13	CDS	CASTEL DI SANGRO	88.5	68.9	0.009	1.720	0.010	1.720	0.007	1.650
14	CER	CERIGNOLA	245.2	224.5	0.001	0.358	0.002	0.452	0.001	0.197
15	CHT	CHIETI	67.1	51.8	0.030	6.850	0.028	7.900	0.017	3.900
16	CLN	CELANO	31.6	12.8	0.091	6.650	0.083	4.890	0.046	7.080
17	CMB	CAMPOBASSO	138.9	116.3	0.003	0.862	0.003	1.330	0.002	0.847
18	CMR	CASTELMAURO	126.9	106.6	0.004	0.836	0.005	0.854	0.003	0.670
19	CNM	CASALNUOVO MONTEROTARO	166.9	146.4	0.002	0.726	0.002	0.829	0.002	0.523
20	CSO1	CARSOLI 1	33.0	29.2	0.018	1.480	0.019	2.350	0.016	1.720
21	CSS	CASSINO	102.7	83.8	0.010	1.390	0.008	1.590	0.003	0.783
22	CTL	CATTOLICA	186.6	177.3	0.003	0.736	0.004	0.731	0.001	0.314
23	FMG	FIAMIGNANO	19.3	16.7	0.027	1.690	0.024	2.860	0.020	1.310
24	FOR	FORLI'	232.3	224.2	0.002	0.668	0.002	0.593	0.001	0.298
25	GNL	GENZANO DI LUCANIA	279.4	255.7	0.002	0.543	0.002	0.569	0.001	0.249
26	GSA	GRAN SASSO (Assergi)	18.0	9.7	0.150	7.970	0.152	9.990	0.118	4.320
27	GSG	GRAN SASSO (Lab. INFN galleria)	22.6	14.3	0.030	3.330	0.021	3.310	0.019	3.260
28	ISR	ISERNIA	109.7	90.2	0.006	0.737	0.007	0.864	0.003	0.476
29	LSS	LEONESSA	39.1	31.8	0.008	0.801	0.010	0.671	0.006	0.738



L'Aquila Earthquake Experience

Figure. Church Santa Maria in Paganica

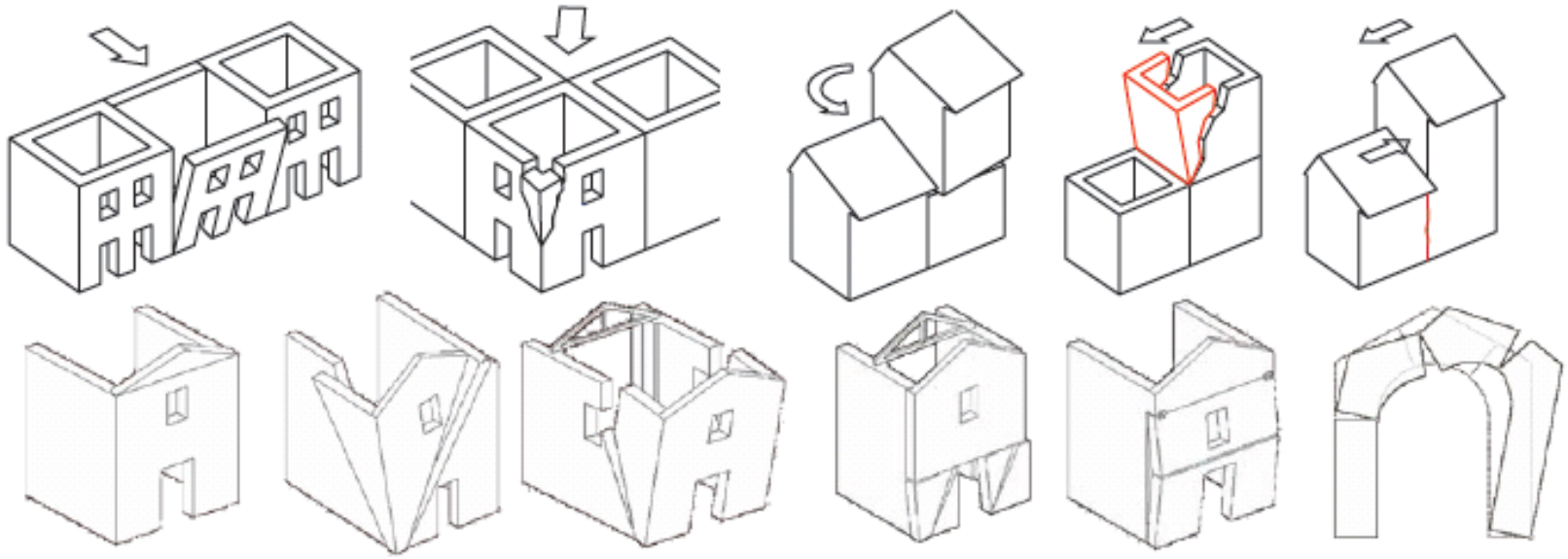
Figure. Provincia Palace (4 Cantoni)

The experience of the earthquake which struck the Abruzzo (April 2009), showed that the type of collapse for existing masonry structures is based on kinematic mechanisms due to loss of equilibrium of walls or assemblies of walls, with out-of- plane mechanisms at the global and local level.

Location of damage mechanisms Macroelements

Macroelement: constructively recognizable part of the building with homogeneous characteristics with respect to the structural behavior. It may coincide sometimes with an architectural and functional part.

The macro-elements interact with each other by showing cracks at the contact area (Bands of influence). Bands of influence are identified by weak or missing links or effects of damage (cracks).



L'Aquila Earthquake Experience

Figure. Basilica of Santa Maria di Collemaggio

It also highlighted the limitations of some traditional reinforcement techniques. Significant damage have been reported from buildings that had previously been consolidated after the earthquake of 1997, particularly due to questionable activities of the technical choices for incorrect or poor execution of the interventions themselves.

Classification of masonry buildings

- 1ª Type – buildings made only with masonry (oldest buildings);
- 2ª Type – buildings made with vertical masonry box supporting horizontal slabs made with beams of different material and not connected with masonry in the edge points;
- 3ª Type – buildings made with vertical and horizontal components well connected each other.

1 Type
Buildings made only of masonry

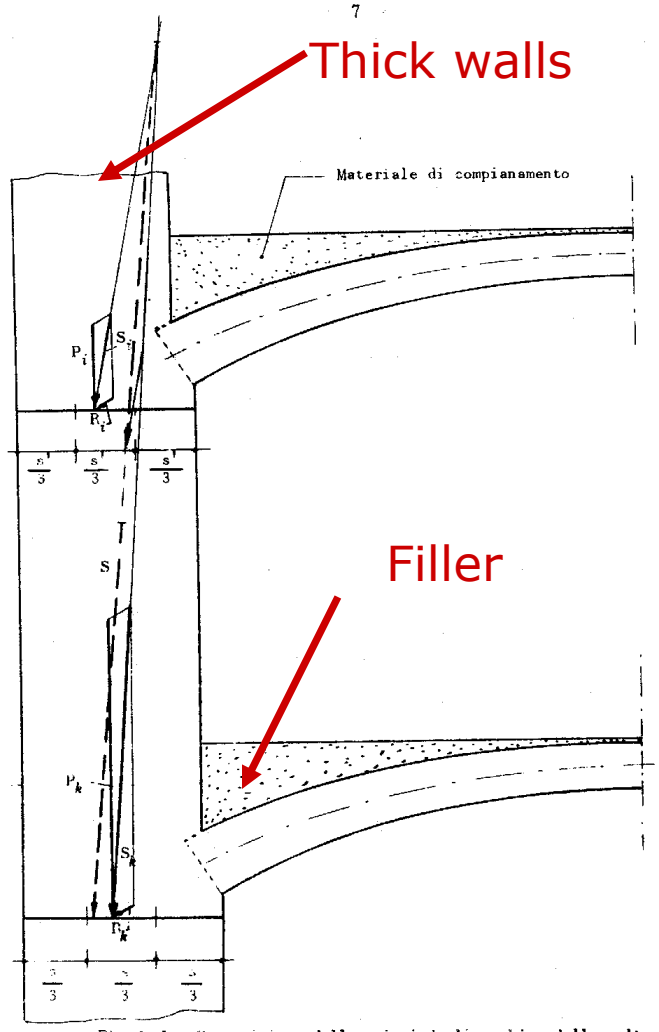
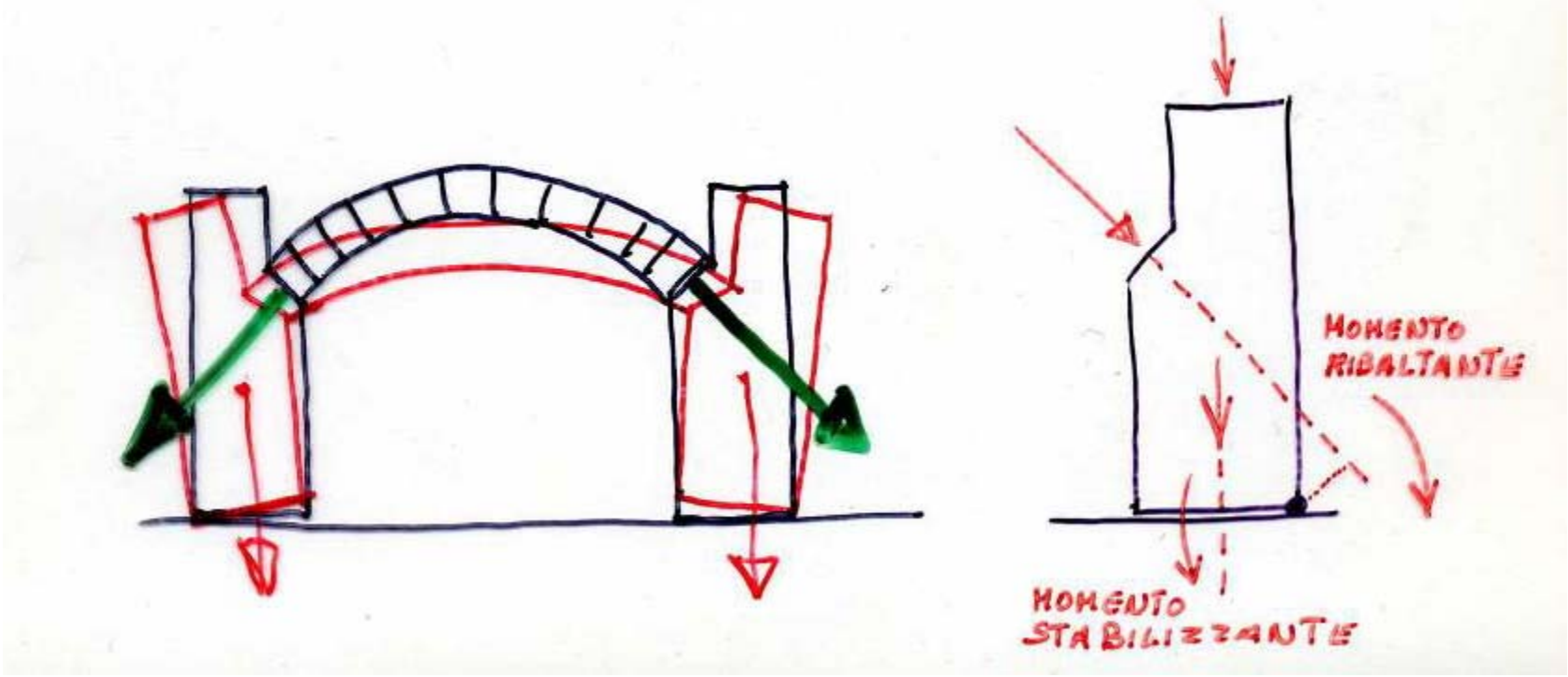


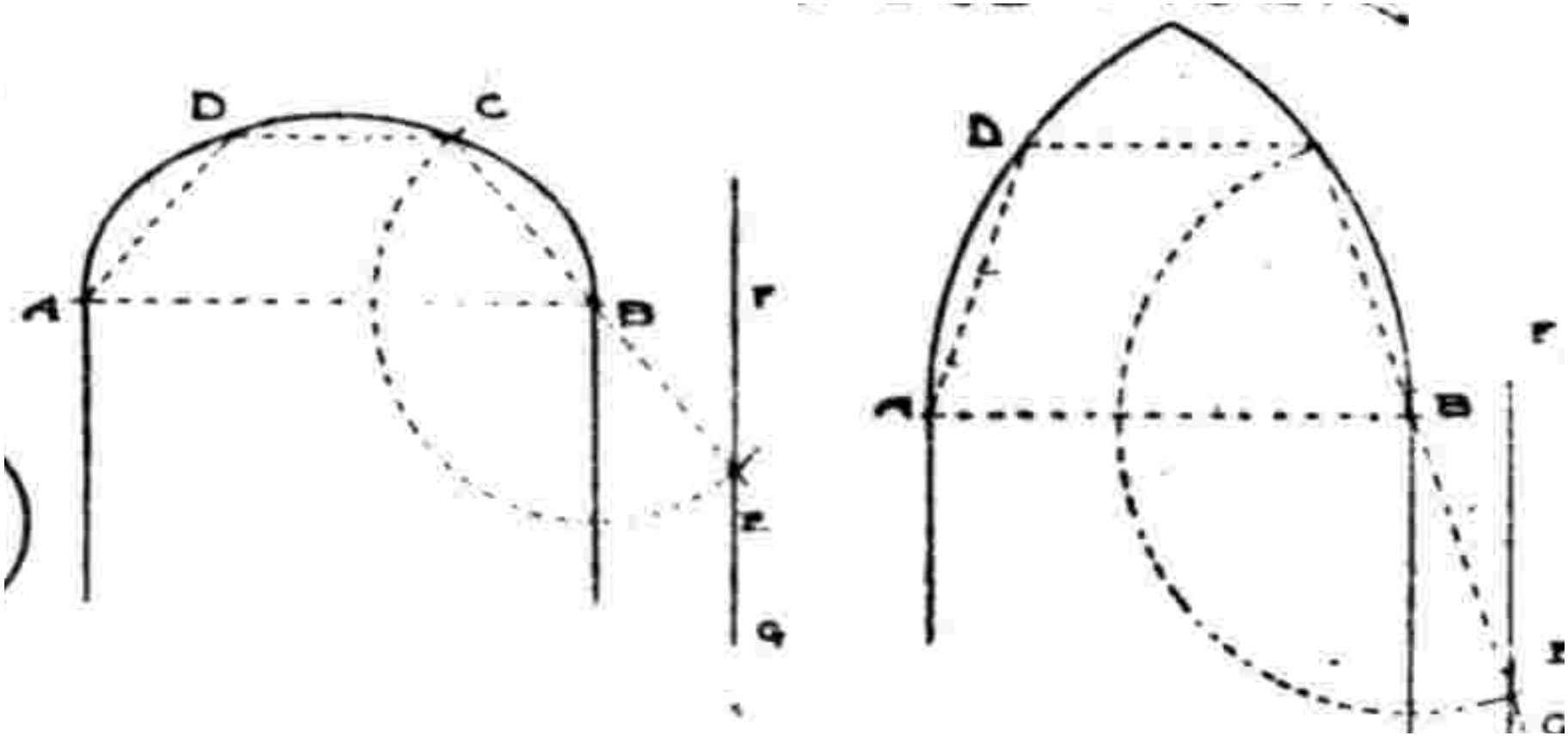
Fig. 1 1.- Composizione delle azioni degli archi o delle volte con il peso delle murature verticali d'imposta.

The masonry (that is not able to resist traction) should support compression loads.
The horizontal floors are realized with arches and vaults that push horizontally the vertical walls. The vertical walls should support gravity loads and the horizontal forces generated by arches.
They work under axial and flexure forces in the typical section.

For centuries the fundamental problem of architects is: which should be the dimensions of the lateral walls in order not to rotate and to support the lateral force of the arch?



Rule of thumb for design of piers



2 Type

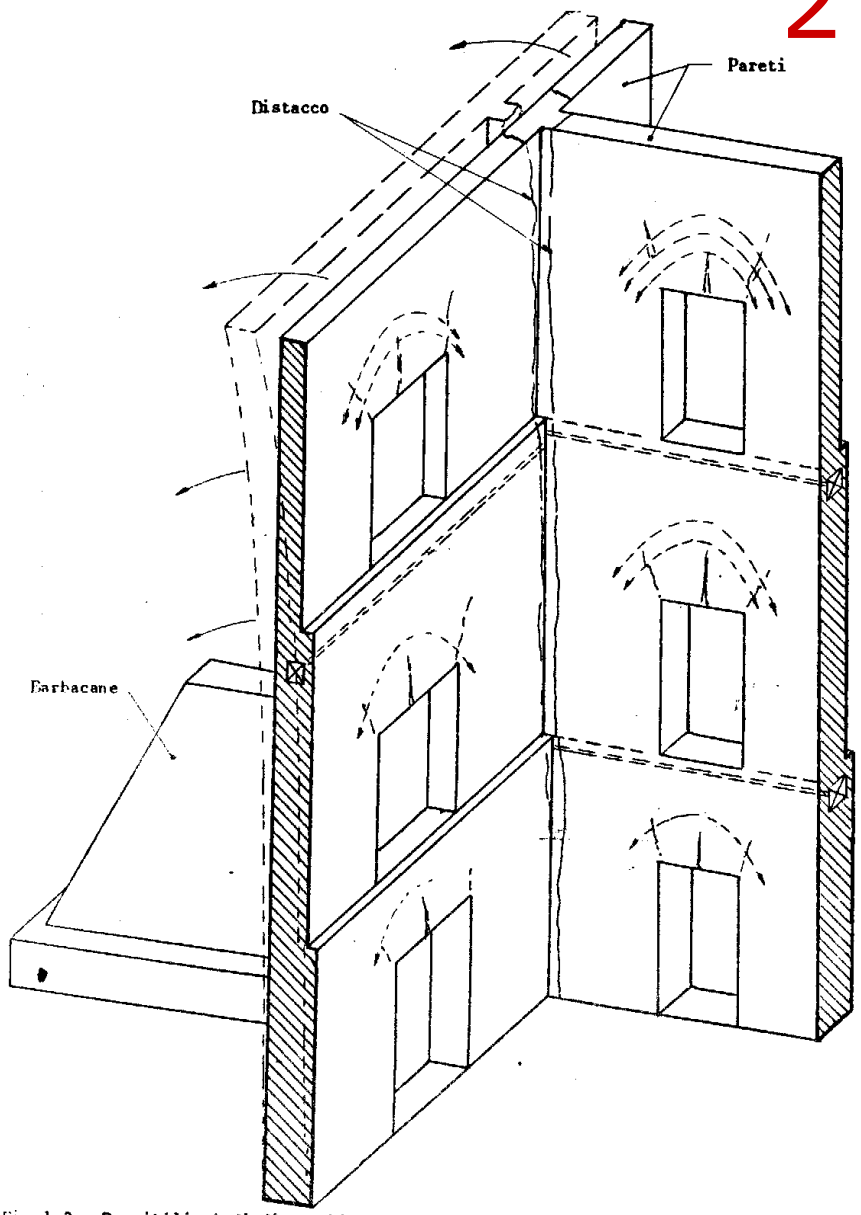


Fig 1 3 - Possibilita' di distacchi tra pareti murarie e formazione di archi sui vani.

Each wall is disconnected from the adjacent one, because there are not horizontal slabs that can support traction and guarantee the link. The external walls are usually not stable because the section reduction is done only on the internal side for esthetic reasons. This generates eccentricity on the gravity loads and a tendency on the external walls to overturn toward the exterior side.

3 Type

- At each floor slab there is an horizontal RC ring beam;
- It avoid the relative displacement between the vertical walls and the floor slab;
- It generates the same rotation between the slabs and the walls;

Masonry in seismic zone

Serious damage (collapse), to the old masonry buildings due to earthquakes, have caused negative impression among non-experts about the appropriateness and adequacy of the masonry as a building technique in the seismic area.

Instead the collapses are due to:

- ☐ poor quality of the materials;
- ☐ poor building construction quality;
- ☐ poor understanding of the structure;
- ☐ lack of accurate design;
- ☐ lack of maintenance;
- ☐ vertical and horizontal development of the building without an accurate analysis of the static behavior of the original building;

Traditional seismic retrofit in historical centers

Figure Cross-tie of the Fortezza Spagnola

Figure Spurs in the convent of Santa Maria di Collemaggio

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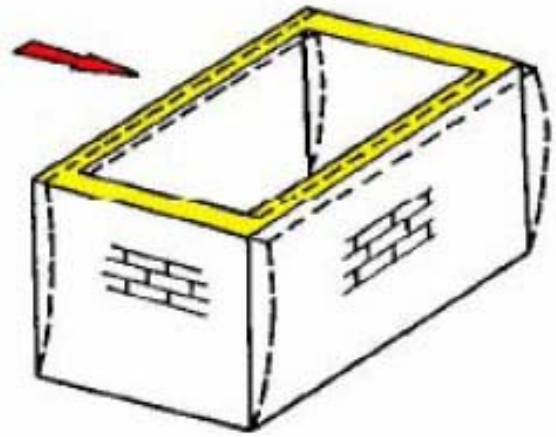
Italian seismic standards

The Italian seismic provisions proposed methods of analysis assuming a "box" behavior and rigid connections between the masonry walls and between masonry walls and floor slabs that were assumed rigid in their plane.



Italian seismic standards

In order to satisfy that assumptions the consolidation techniques could be:

a)Replacement of the wooden floor and roof structures with concrete structures;

b) Insertion of RC ring beams on every floor in the masonry;

c) Use reinforced plaster and/or injections of cement mixtures to increase the shear strength of masonry;

Limits of the Italian seismic standards

Several historic buildings retrofitted in recent decades, have suffered partial an total collapses during L'Aquila earthquake in Abruzzo due to the incompatibility of materials and intervention techniques used.

Out-of-plane collapse triggered by the roof

Damage:
• local collapse in the top of the walls of the tympanum; • collapse isolates.;
Mechanism:
• rolling out the plan of the facade, due to the hammering of the ridge beam;
Structural causes:
• Roof not effectively connected to the masonry.

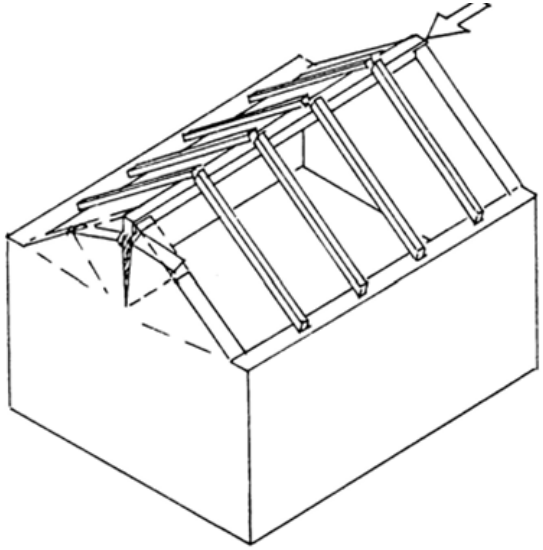


Figure. Convent of Santa Maria di Collemaggio

Lack of technical knowledge and ineffective interventions

L'Aquila earthquake has showed that:

a) The analytical models must be adapted to different types of buildings and materials taking into account the actual structural behavior;

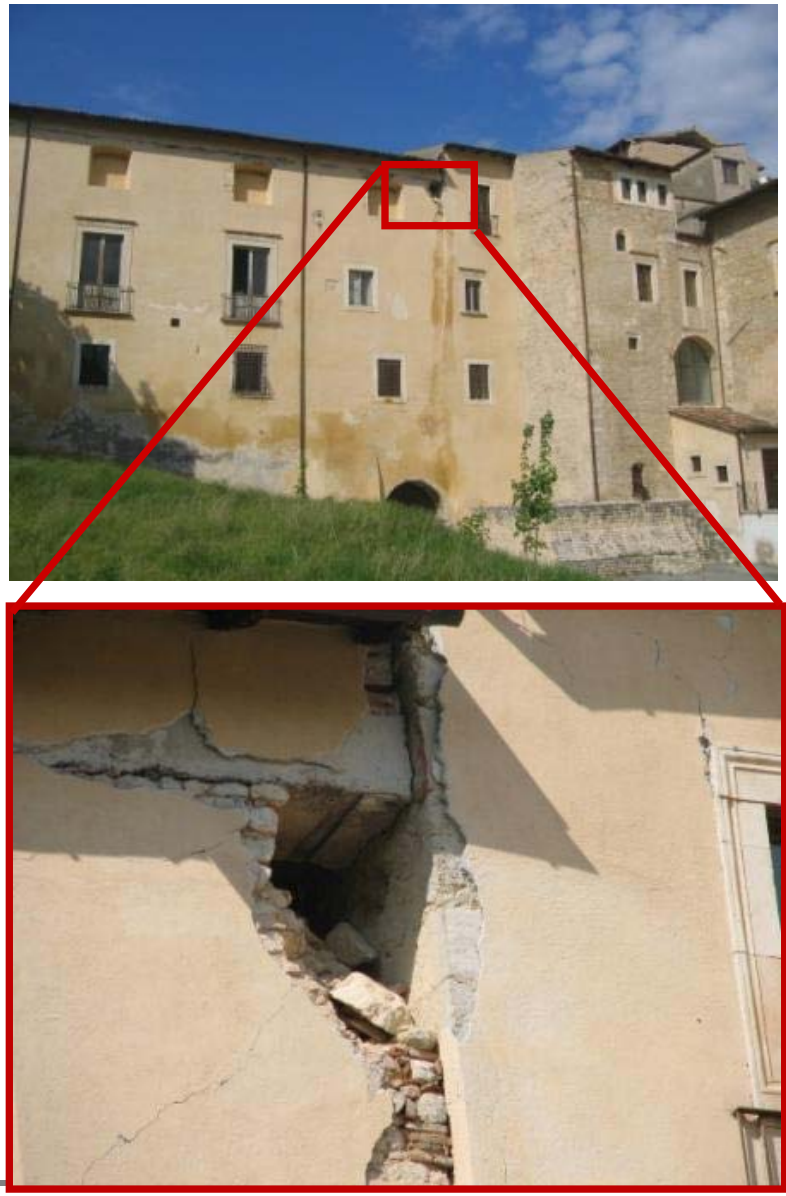
b) The intervention techniques should also be adjusted, calibrated and improved;

a) Replacement of the floor slabs and roofs and inclusion of RC ring beams in the masonry

Damage observed:

- lack of or poor connection between the ring beams and masonry;
- eccentricity of the loads on each floor;
- collapse of walls for out-of-plane forces;

Poor connection between ring beam and masonry



Collapse of half building triggered by the RC roof

c) Reinforced plasters

Most common errors:

(a) lack of connections between rebar applied to the perpendicular walls;

(b) lack of overlap between adjacent rebar;

(c) lack of uniform distribution of the rebar;

(d) low durability;

Figure Onna

Figure Sulmona

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- Damage to RC buildings;

Fortezza Spagnola

Fortezza Spagnola

Fortezza Spagnola

Damage:

- partial collapse of the floor slab;
- Partial collapse of the roof;
- Partial collapse of the upper lateral wall;
- Severe cracks on the vertical walls;
- Severe overturning of the arcades (loggiato) and of the columns on the ground floor;
- Severe damage to historical heritage inside the National Museum of Abruzzo;

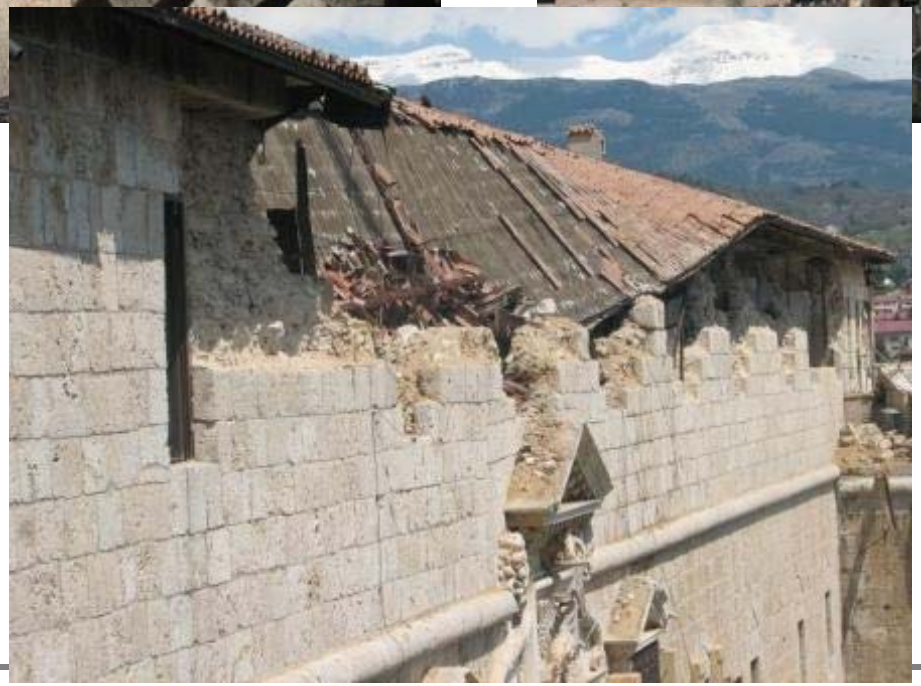
Estimation of Economic losses:

- 50.000.000 Euro;

Estimated Recovery time:

- 8 years;

Fortezza Spagnola

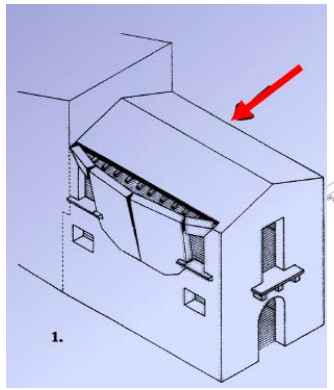


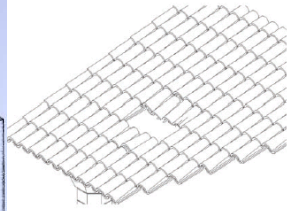
Damage to roof coverage

Damage:
- Partial Collapse of the roof coverage;

Mechanism:
- rolling out the plan due to horizontal flexure of the upper part of the façade;

Structural causes:
- Poor connection between the roof slab and the lateral wall weaker due to the presence of openings;
- Poor quality of the masonry;

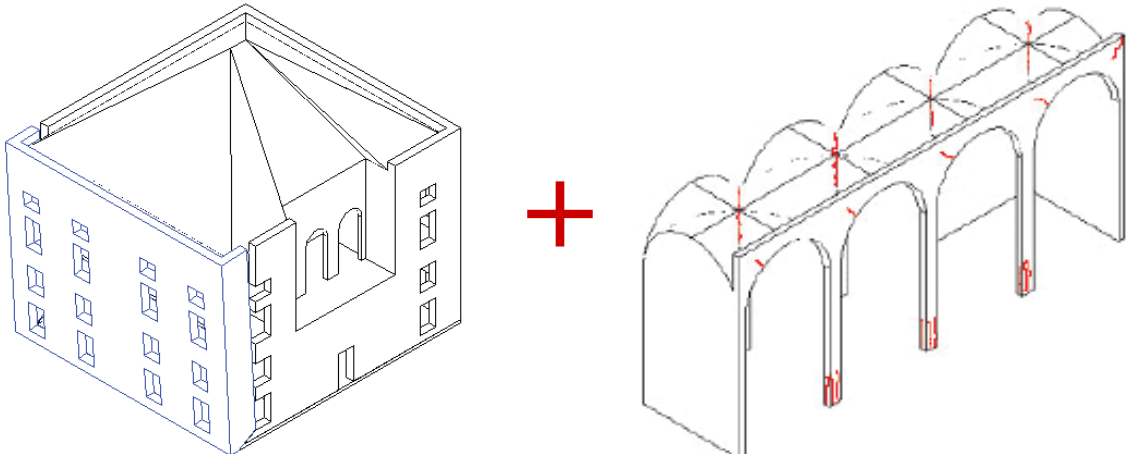




Overturning of the Arcade

Damage:

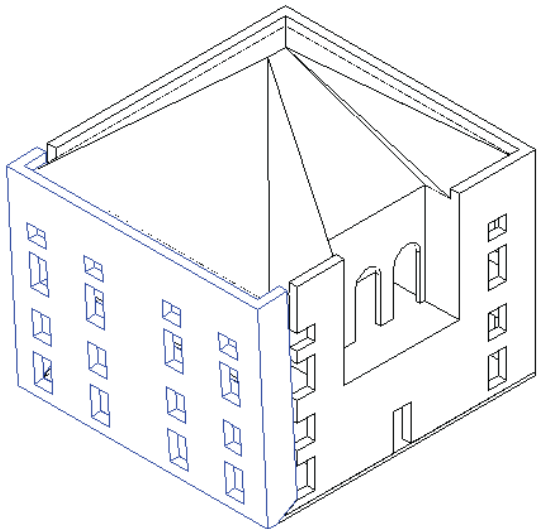
• overturning of the internal arcade facing the internal yard and severe damage in the internal columns of the arcade;



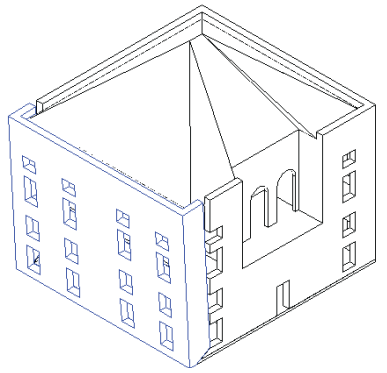
Overturning of the wall

Damage:

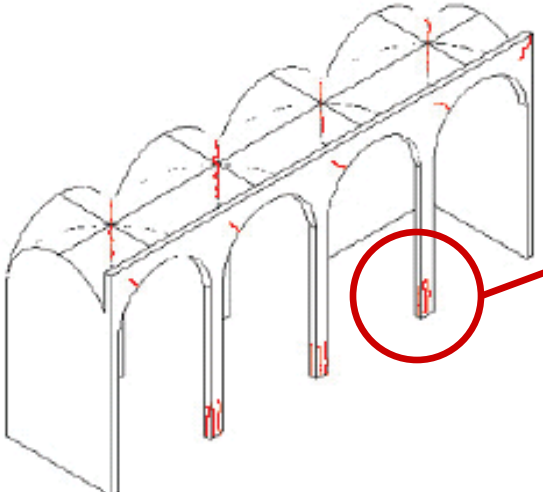
• overturning of the internal arcade facing the internal yard and severe damage in the internal columns of the arcade;



Signs of overturning wall



Damage to arcades



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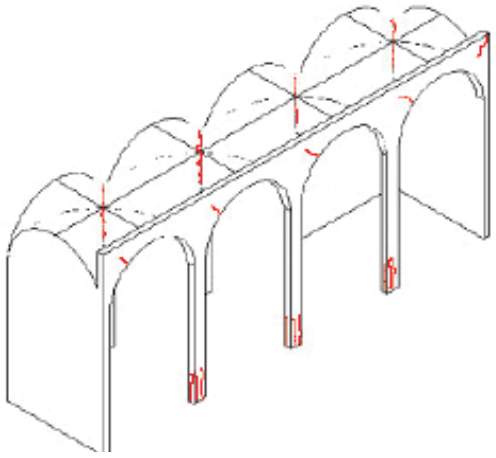

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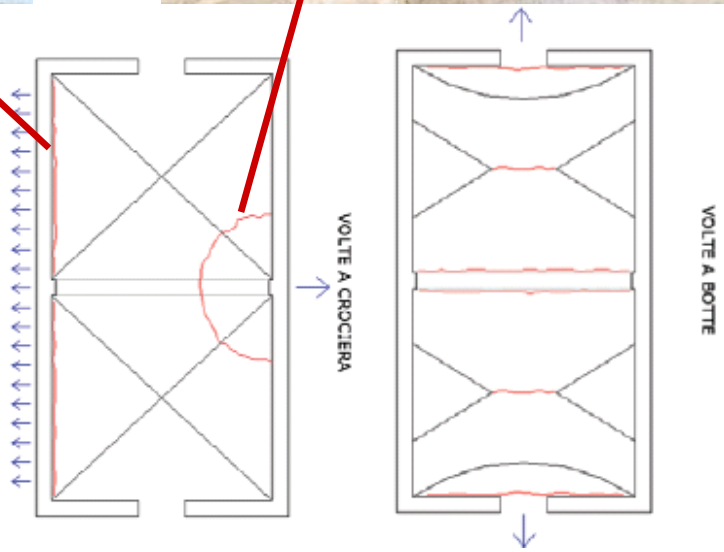
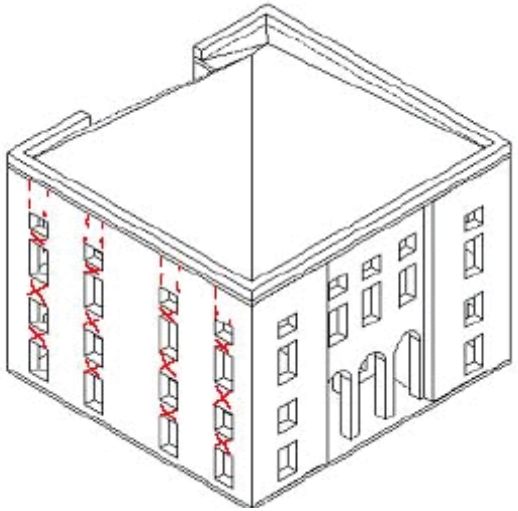


Damage in the wall strips

Damage:

• typical cross cracks in the wall strips above and below the window openings;



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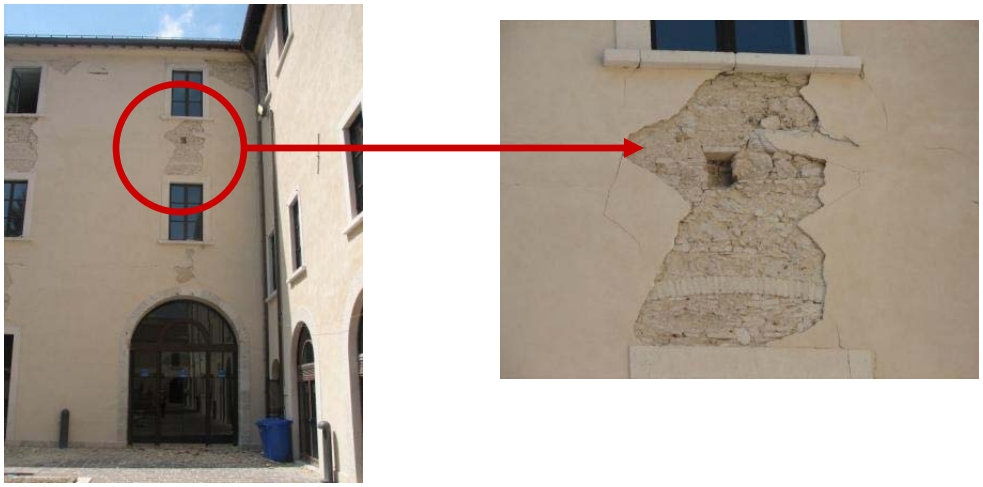
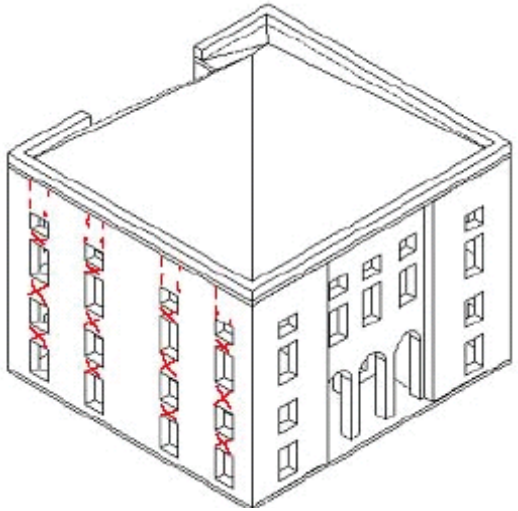
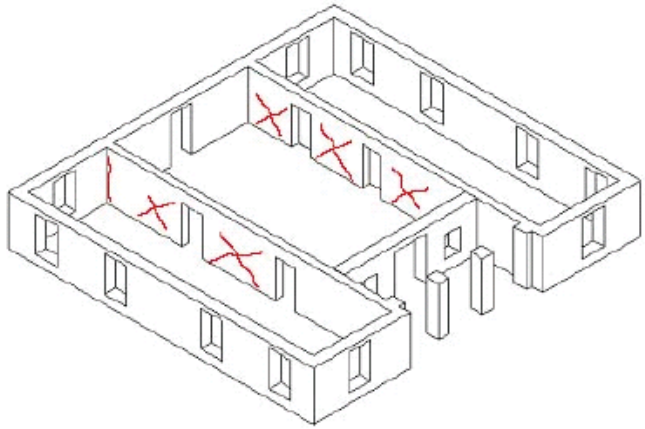




Damage in the lintels (Architrave)

Damage:

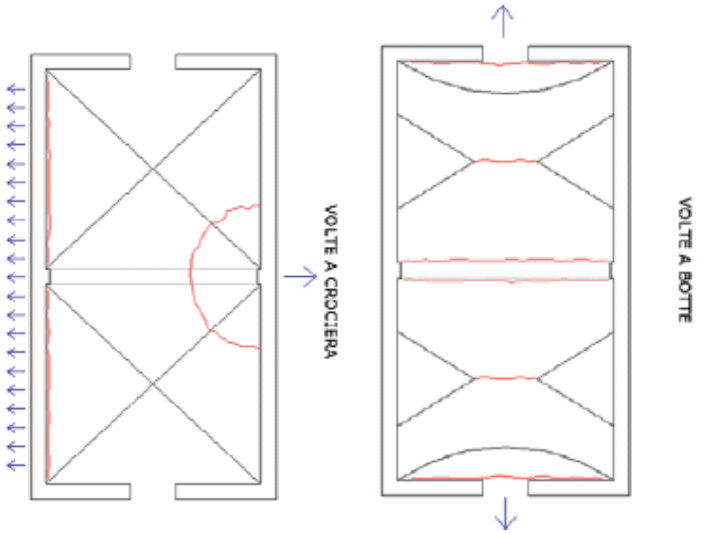
- shear cracks in the internal walls strips in correspondence of the door openings;



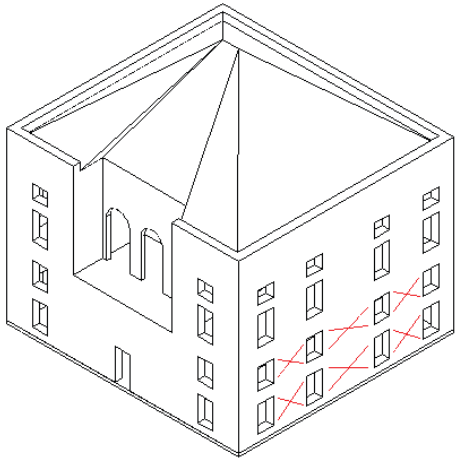
Damage to Vaults

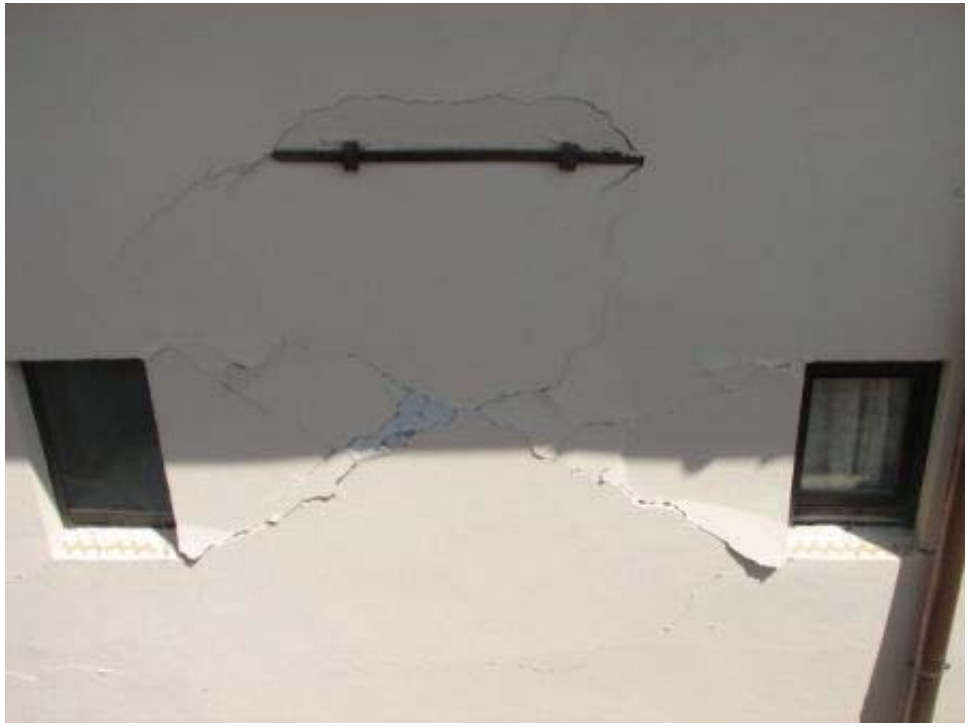
<u>Damage:</u>
- cracks in the arch, the cross vaults and barrel vault;

<u>Structural causes:</u>
- Rotation of the lateral walls.



Damage in the lateral strips walls “maschi murari”





Damage to the stairs

Local mechanisms-Poor quality of Masonry

In existing masonry buildings local collapses appear because of loss of equilibrium of part of the walls.

Figure Convento Santa Maria di Collemaggio

Figure Fortezza Spagnola

Damage on the third floor

Damage to National museum of Abruzzo

Damage to National museum of Abruzzo

Shore-up interventions

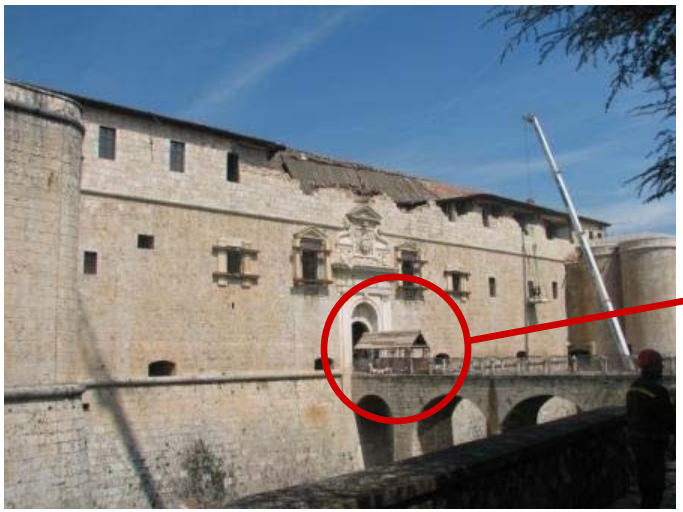
Shore-up interventions








Shore-up interventions



Basilica Santa Maria di Collemaggio

Plan and longitudinal view

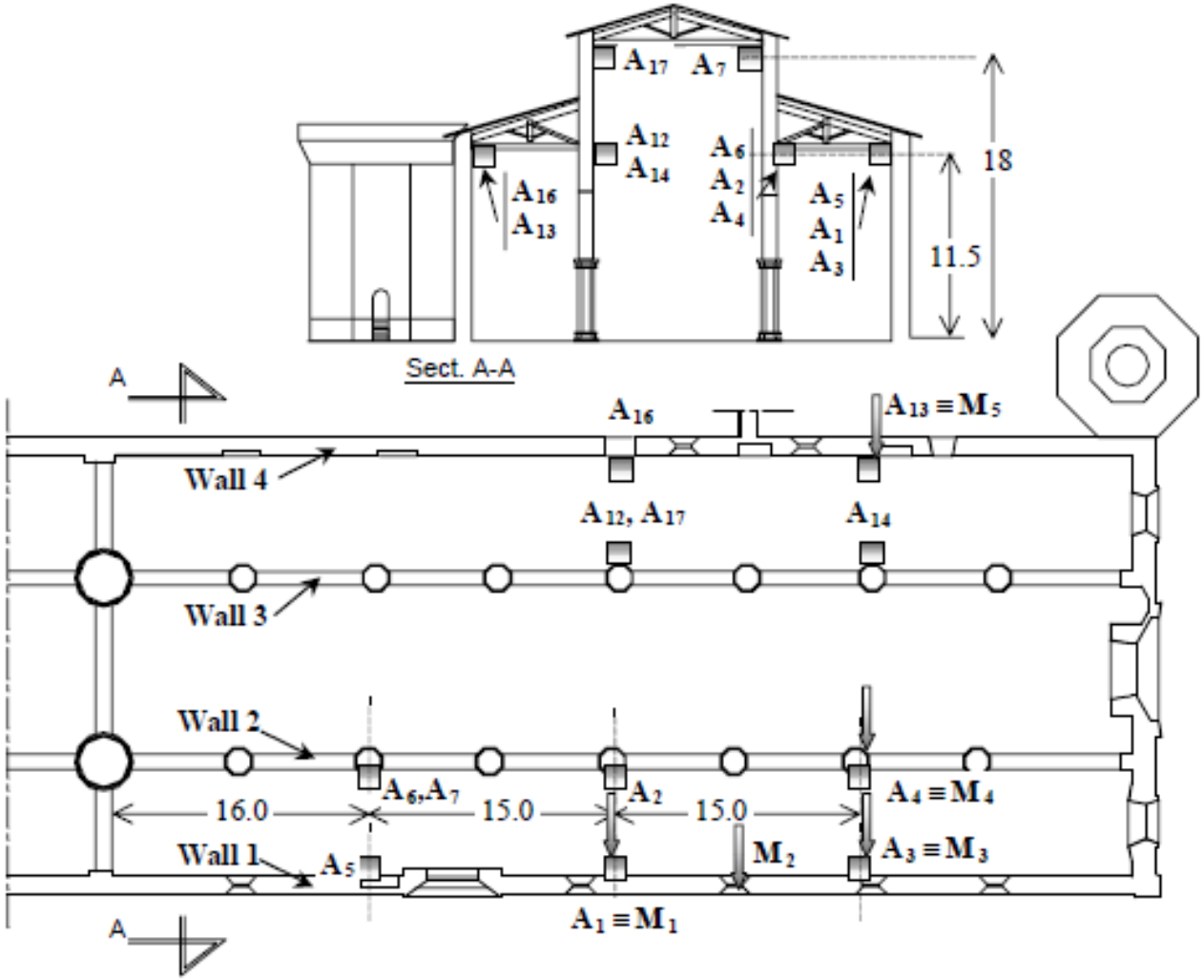


Figure. Accelerometers (A) and hammer impact points (M) (Antonacci et al. 2001)

Santa Maria di Collemaggio (XIII sec)

Figure. Basilica Santa Maria di Collemaggio

Damage:

- Collapse of the vault of the transept;
- Collapse of the Triumphal arches;
- Collapse of the "tamburo" and of the Dome;
- Collapse of the roof elements of the transept;
- Severe cracks with imminent collapse in the apse and in the presbitery;
- Moderate cracks in the tower and the tower room;

Estimation of Economic losses:

- 10500000+5500000 Euro;

Estimated Recovery time:

- 36 months+24 Months 5yrs;

Interior of Santa Maria di Collemaggio

Altar

La Porta Santa

Facade of the Basilica

Figure. Façade before the earthquake

Figure. Façade at the moment of the earthquake

Details of the Facade scaffolds

The structural scaffolds supported the front façade avoiding its collapse.

Seismic retrofitted…

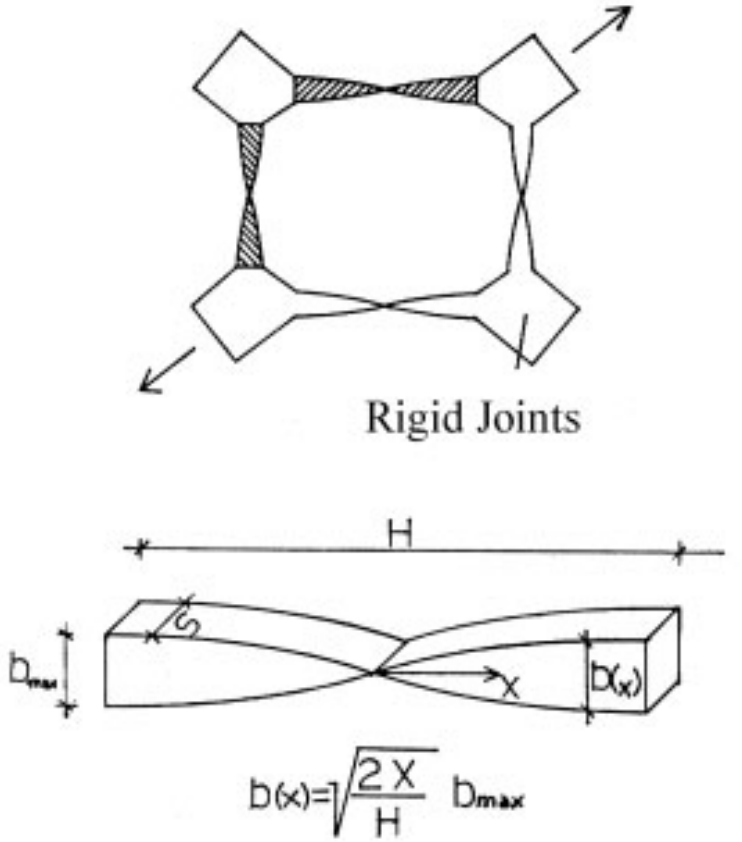


Figure. Quadrilater steel hysteretic damper

The damper dissipates energy through uniform yielding while the tendons remain always in tension.

Pall friction dampers (1985)

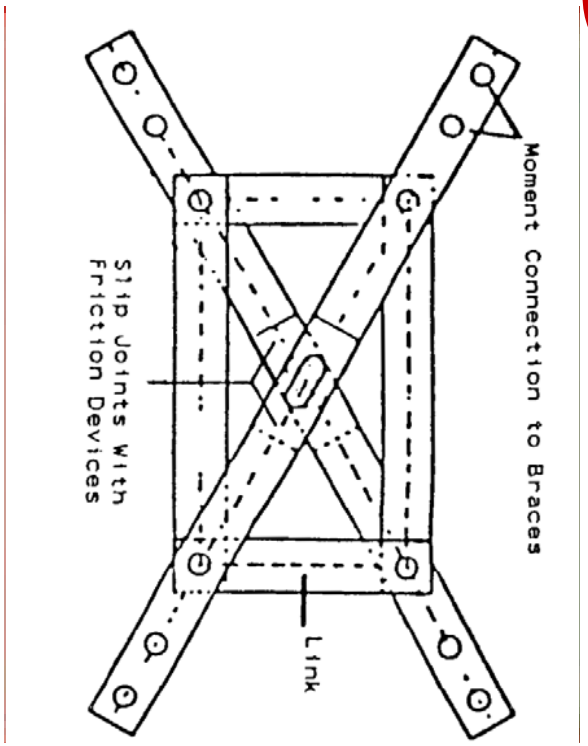
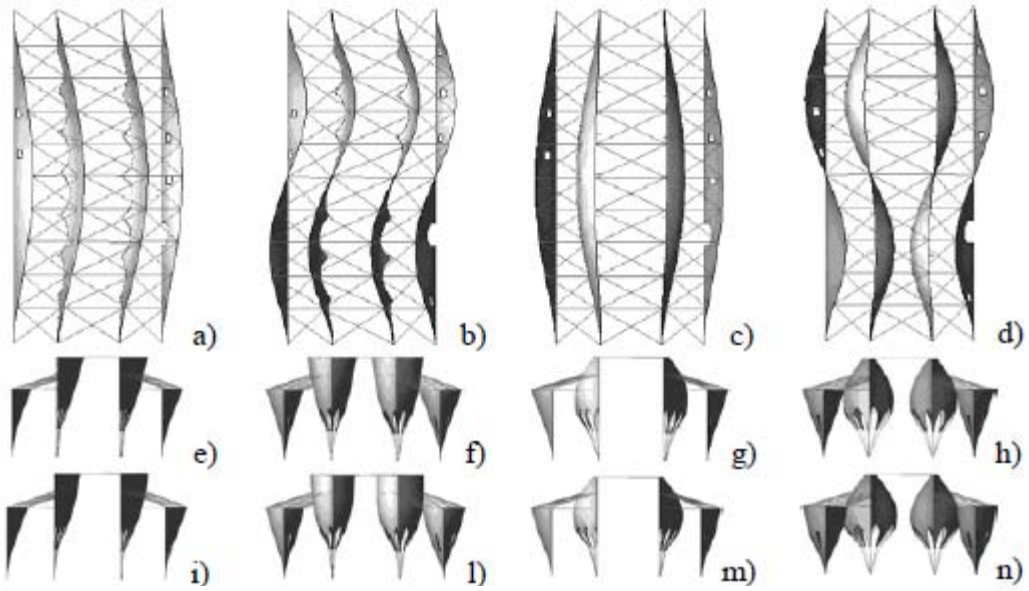


Figure. Pall Friction damper (Filitrault et al. 1985)

Figure. Quadrilater steel hysteretic damper (Ciampi et al. 1993)

Not an original idea, but inspired by Pall Friction dampers that were tested in 1985 and applied in the first building in 1987 in Canada

Modal frequencies and mode shapes of the FE model



Model	E_1/E_2	1st (Hz)	2nd (Hz)	3rd (Hz)	4th (Hz)
1	0.2	1.01	1.61	2.18	2.53
2	0.6	1.10	1.61	2.45	2.47
3	0.8	1.20	1.79	2.68	2.73
1R	0.2	1.29	2.13	2.30	2.82
2R	0.6	1.37	2.20	2.59	3.04
3R	0.8	1.41	2.24	2.66	3.12

Figure. Modal frequencies and mode shapes (Antonacci et al. 2001)

Experimental transfer functions

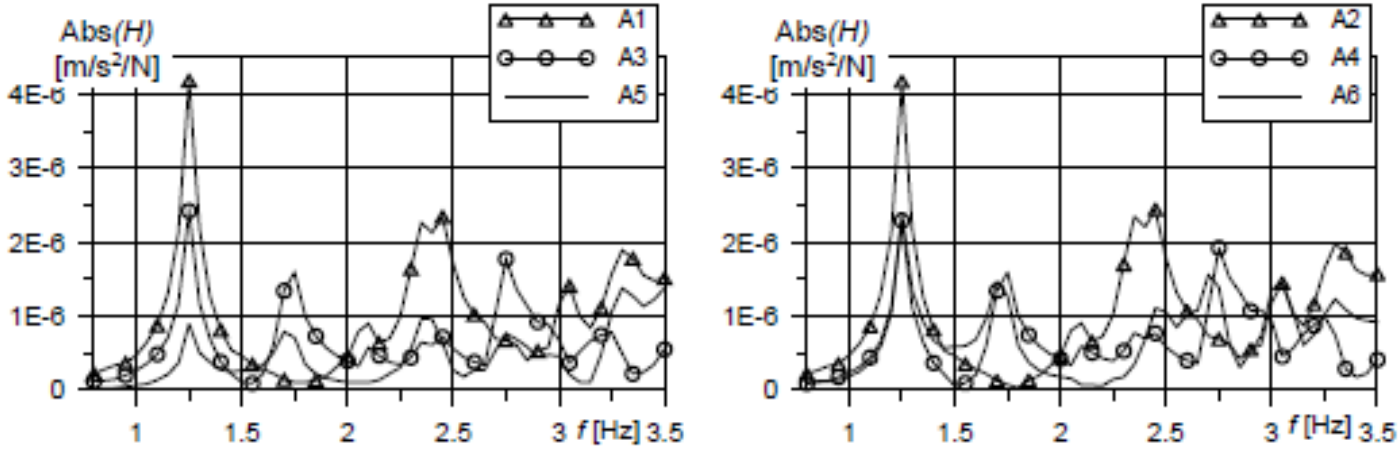


Figure. Transfer functions from hammer test M2 before retrofitting (Antonacci et al. 2001)

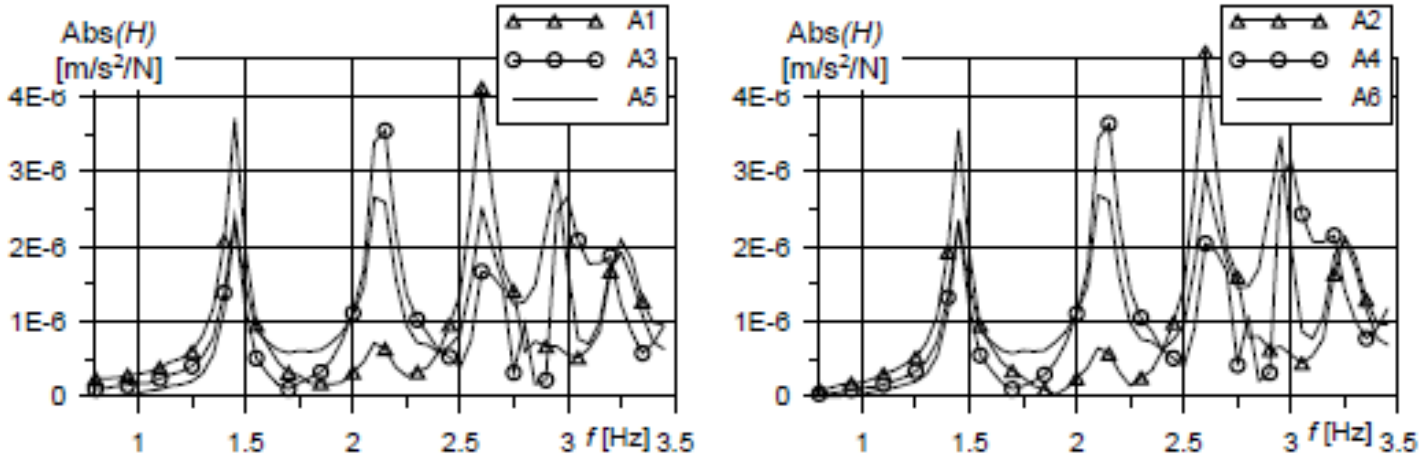


Figure. Transfer functions from hammer test M2 after retrofitting (Antonacci et al. 2001)

Seismic retrofitted…

Figure. Location of one of the two hysteretic steel dampers at the edge of the nave

The steel dampers connected the two walls together making the nave laterally stiffer than the transept

Seismic retrofitted…

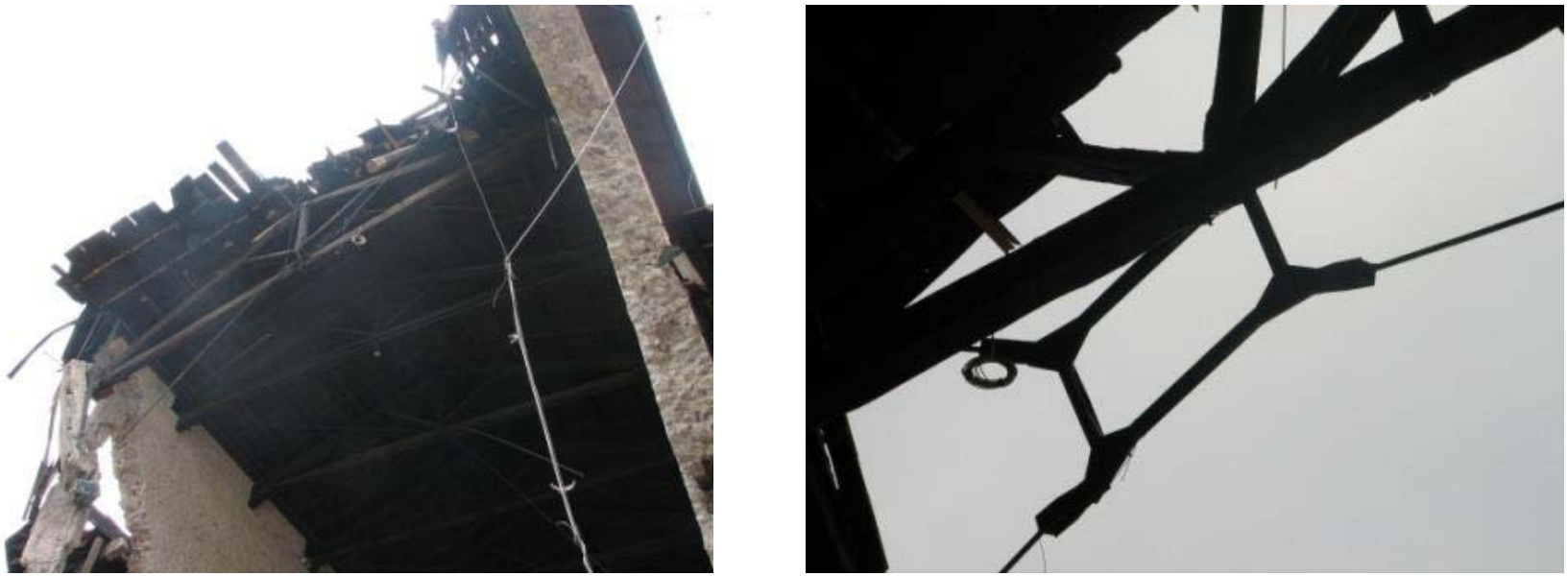


Figure. Hysteretic steel dampers located close to the transept

The steel dampers connected the two walls together making the nave laterally stiffer than the transept

Transept

Shore-up interventions

Figure. Basilica Santa Maria di Collemaggio

First emergency intervention of confinement of the columns to increase their axial capacity;

Basilica Santa Maria di Collemaggio

Palazzo Margherita, L'Aquila, XIII sec.

Damage:

- Overturning of the external walls;
- Damage to the arcades "Loggiato" and to the columns;
- partial collapse of the floor slab on the second floor;
- Damage on the strips walls;
- The internal vaults in the stairs are seriously damaged;
- Damage in the facade, due to the hammering of floor beam;
- The civic Tower presents cracks at the basement level

Estimation of Economic losses:

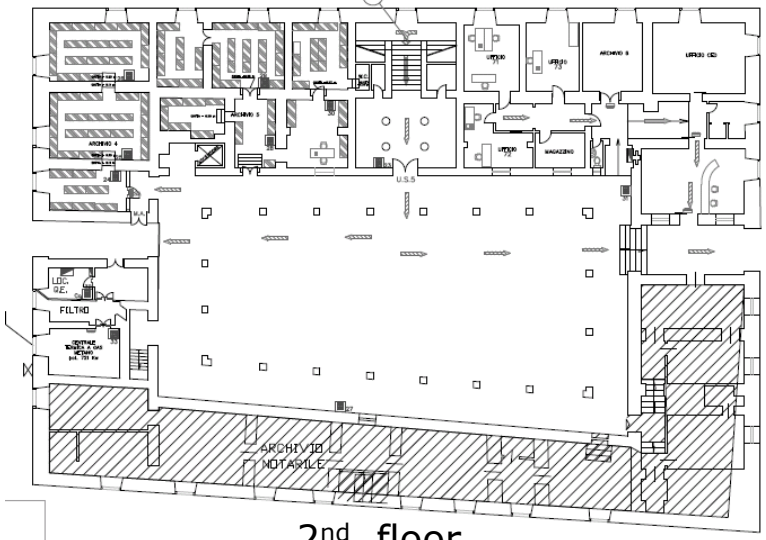
- 4.800.000 Euro;

Estimated Recovery time:

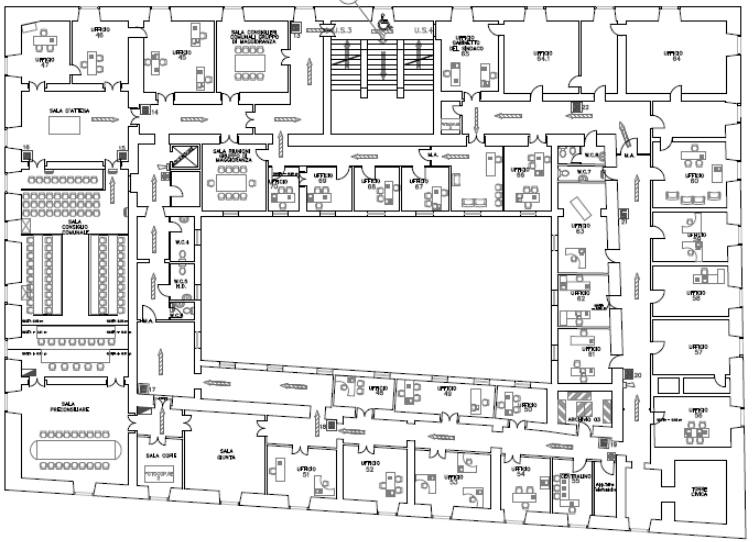
- 40 months;

Plan views

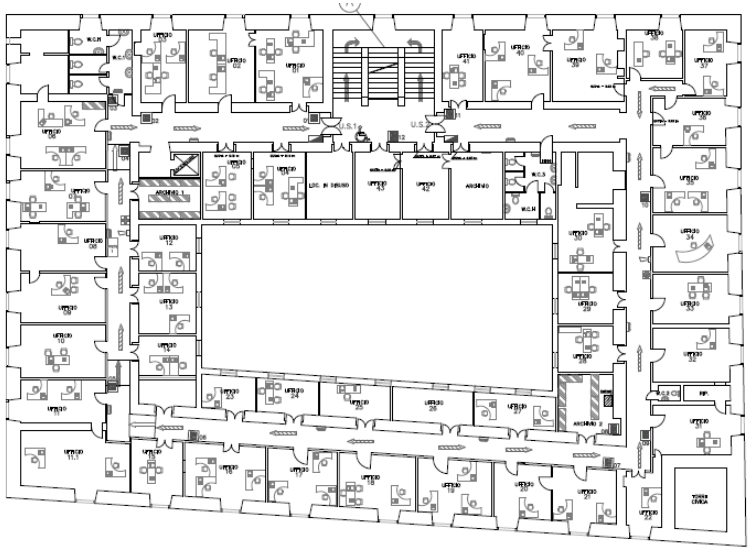
Ground floor



1st floor



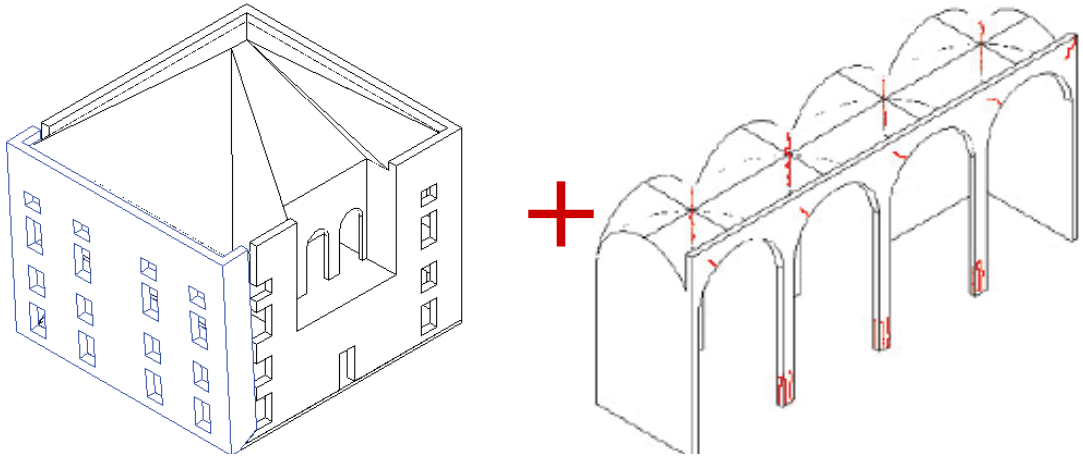
2nd floor



Damage to Arcades

Damage:

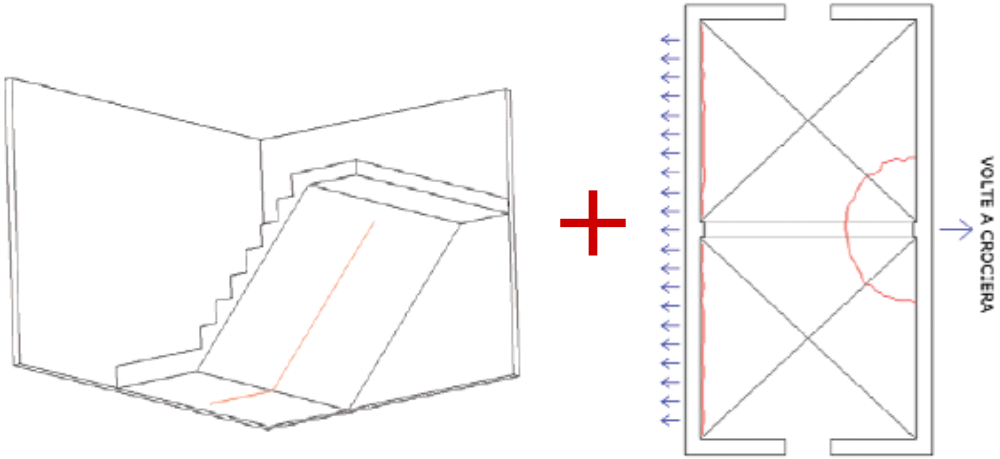
•Overturning of the internal arcades "Loggiato" and of the columns;



Damage to the stairs

Damage:

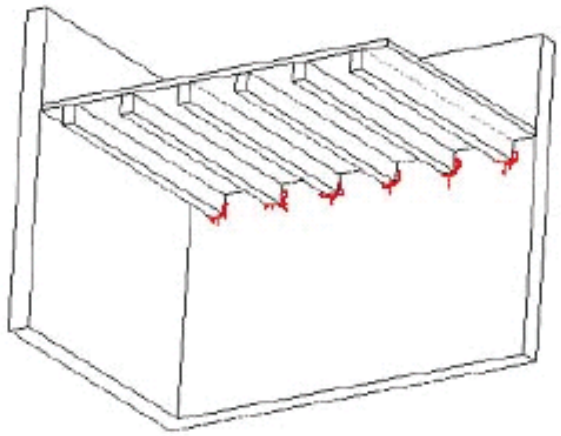
• shear cracks in the stairs especially at the second and third floor level;



Damage to the stairs

Hammering of the floor beams

Damage:
• local damage in correspondence of the wall strips in the facade;
Mechanism:
• damage to the front facade, due to the hammering of the floor beams;
Structural causes:
• Floor slab not effectively connected to the wall masonry.

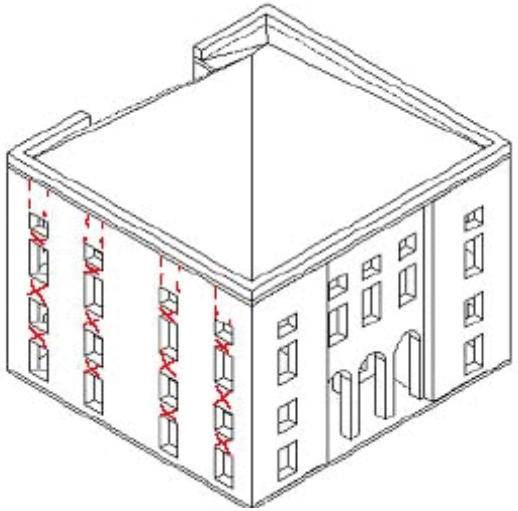


Hammering of the floor beams

Damage in the wall strips

Damage:

• typical cross cracks in the wall strips above and below the window openings of the internal arcade;



Damage in the wall strips

Damage:

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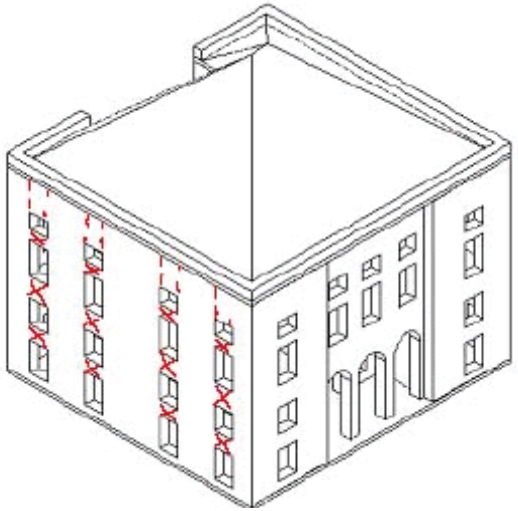
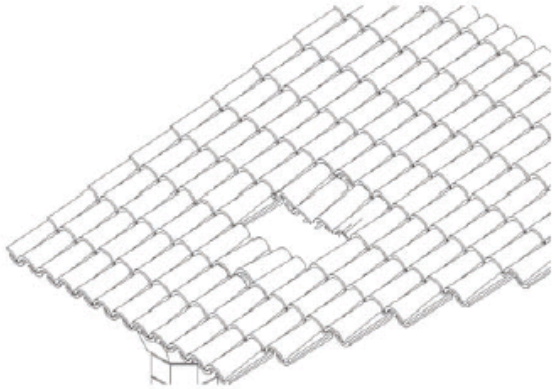


Damage to roof coverage

Damage:
• Partial sag of the roof coverage and dislocation of tiles;



Damage to roof coverage

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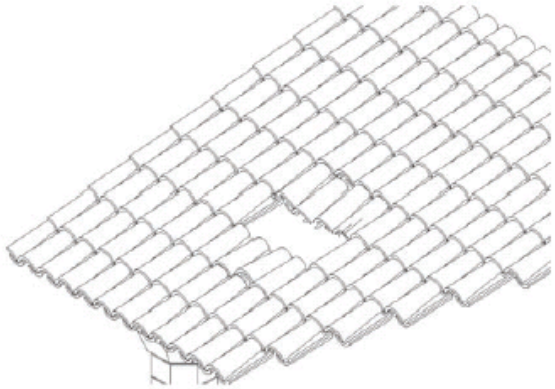
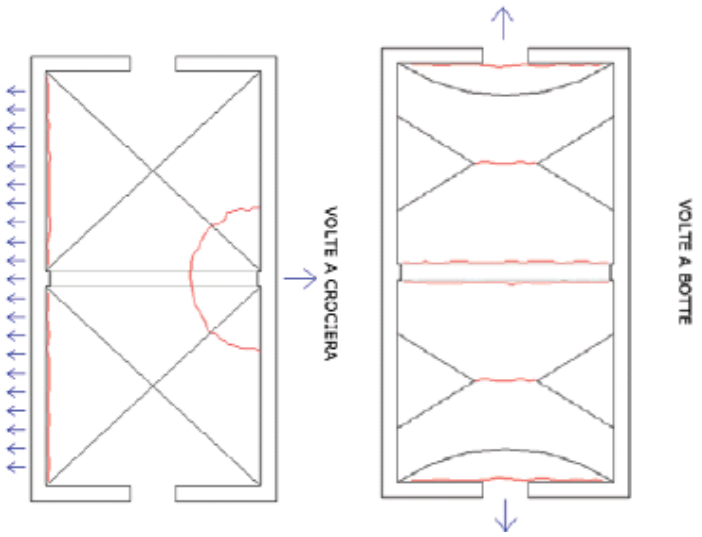


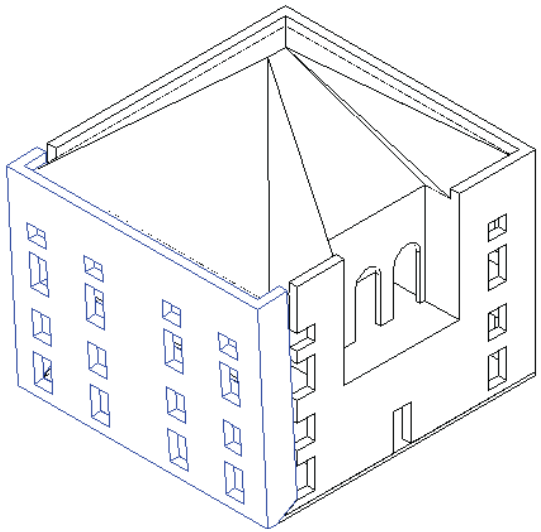
Damage to Vaults

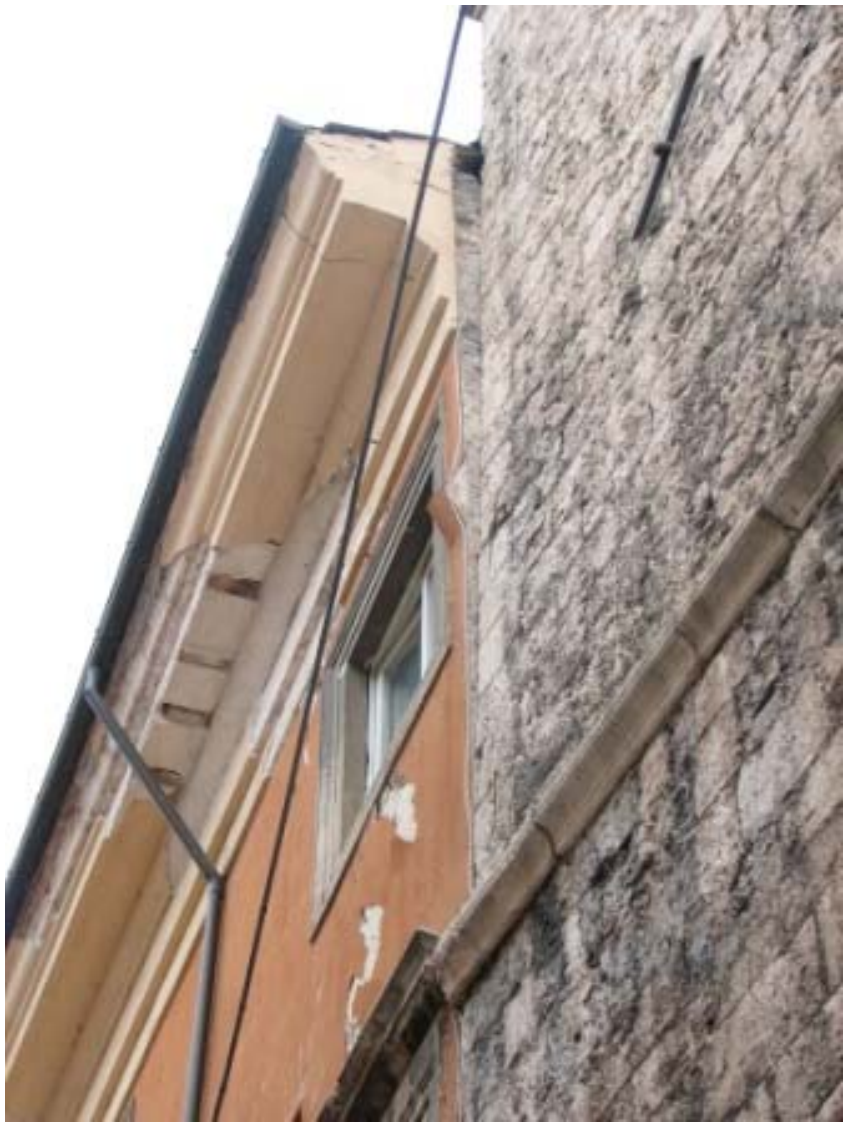
Damage:
• cracks in the arch, the cross vaults and barrel vault;
Structural causes:
• Rotation of the lateral walls.



Overturning of the wall

Damage:
• overturning of the external wall;
Structural causes:
•Eccentric gravity loads due to section reduction;





Cross-Tie of the Civic Tower

Damage due to shape irregularities

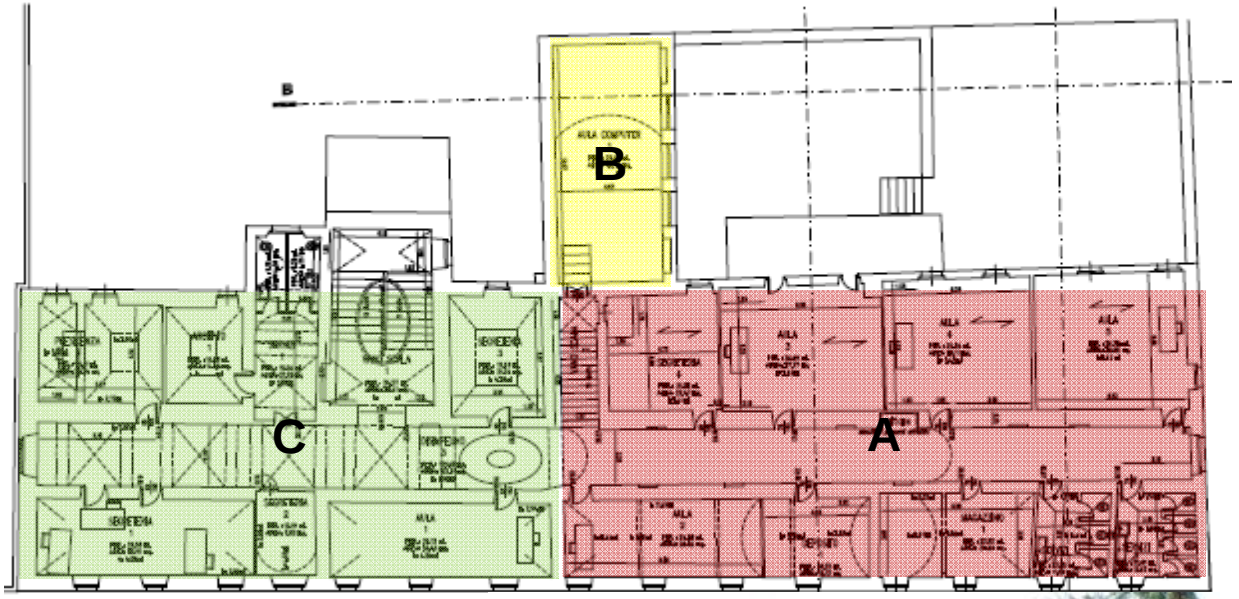
Internal vertical cracks

Ex-monastery of the Lauretana (XV sec.)

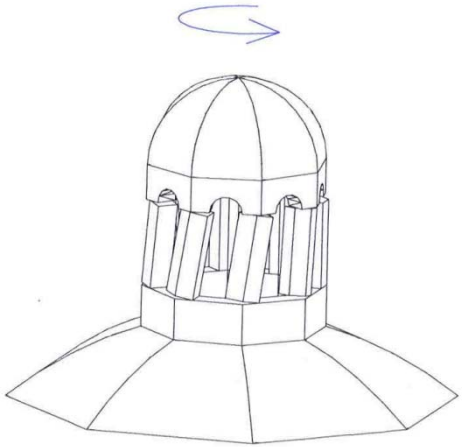
Damage:

- Severe risk of collapse of the lantern;
- Damage in the attached body;
- Damage in building A and B due to hammering of the ridge beam;
- Longitudinal cracks in the barrel vault of the corridor in building A;
- Overturning of the lateral walls of building C facing the internal back yard;
- Collapse of the internal gypsum walls;
- Collapse of the confinement wall of the garden;

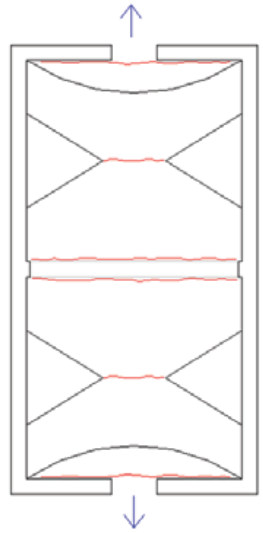
Plan and section view

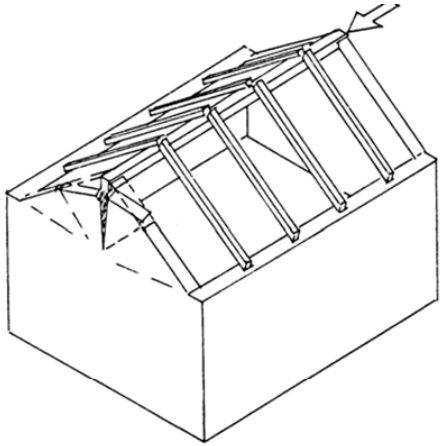


Torsion mechanism of the lantern

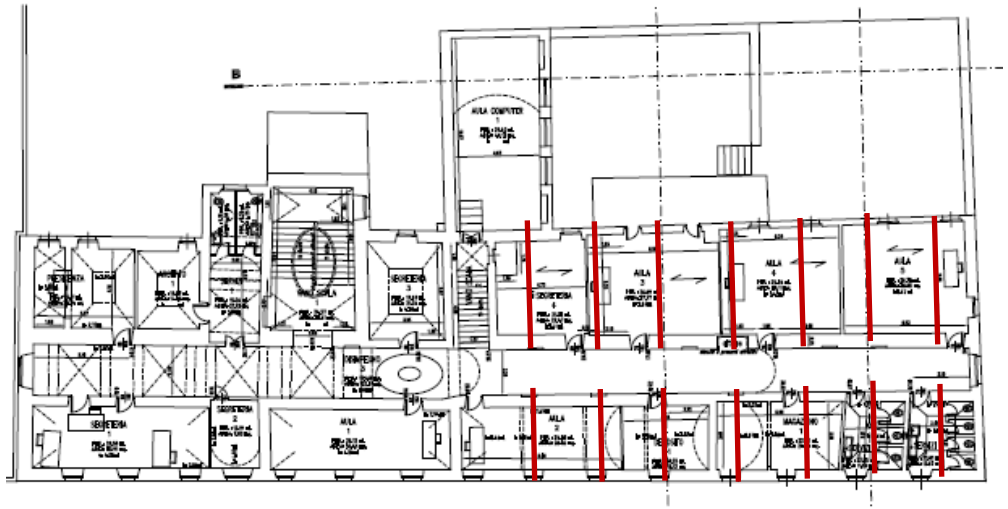


Hammering of the ridge beam





Cross-ties



Out-of-plane wall mechanisms of building B

Other damages

Palazzetto dei Nobili, L'Aquila, XVII sec.

Damage:

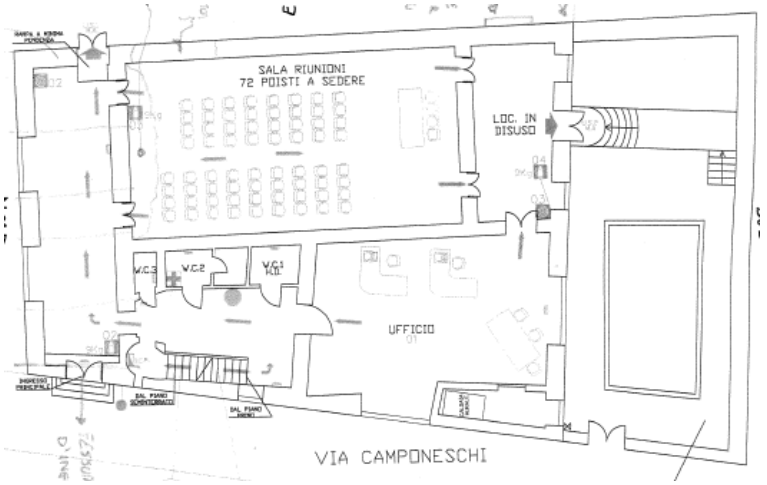
- Damage to Vaults
- Damage to floor slabs;
- Damage on the main masonry structural walls;

Estimation of Economic losses:

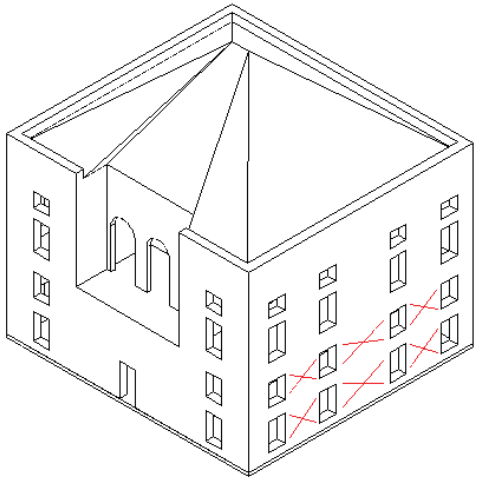
- 900.000 Euro;

Estimated Recovery time:

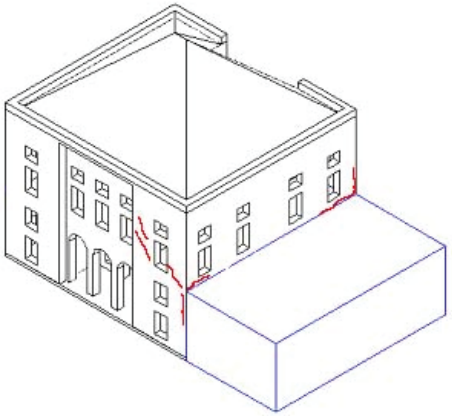
- 24 months;



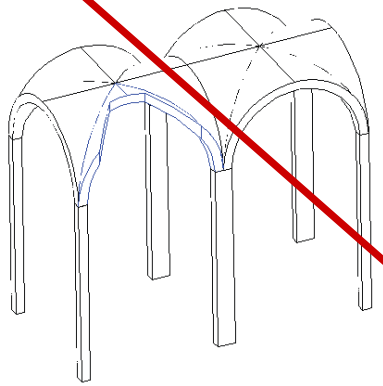
Damage to external walls



Damage to external walls



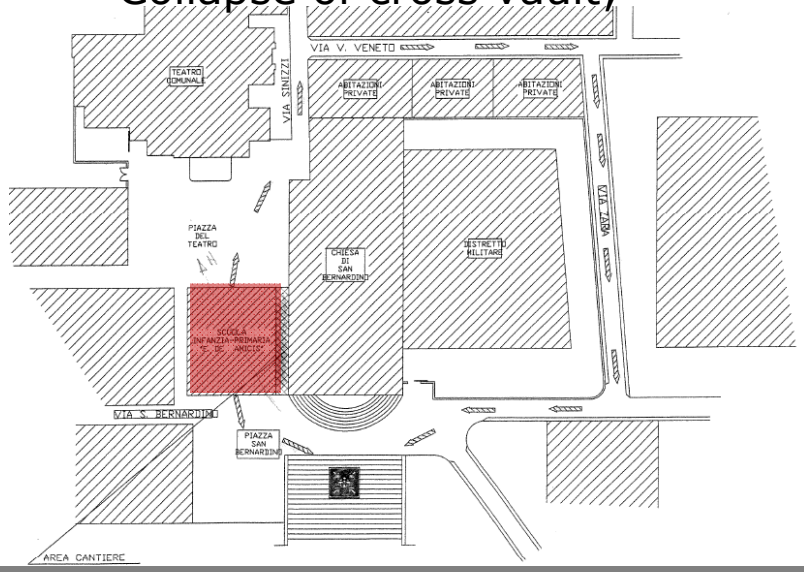
Partial collapse of the wooden cross vault



School De Amicis, L'Aquila, (XV sec)

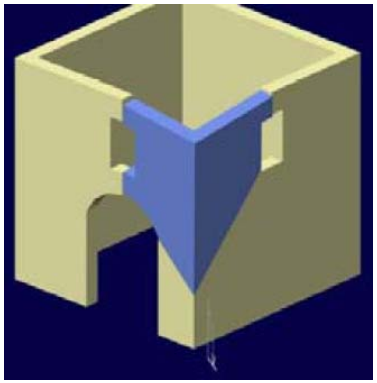
Damage:

- Partial collapse of the roof;
- Partial collapse of the upper lateral wall;
- Cracks in the internal walls with partial collapse of ceilings;
- Dislocations of horizontal slabs;
- Collapse of cross vault;

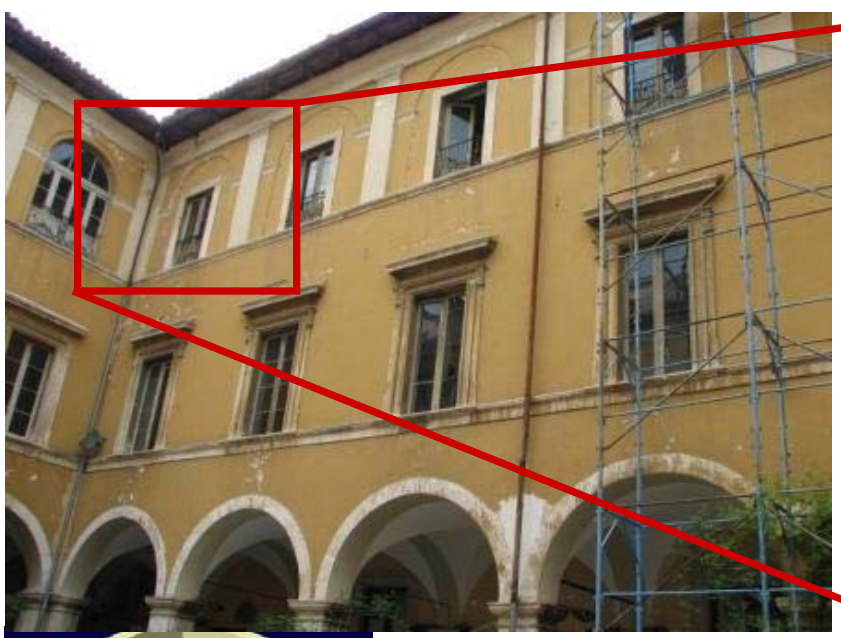


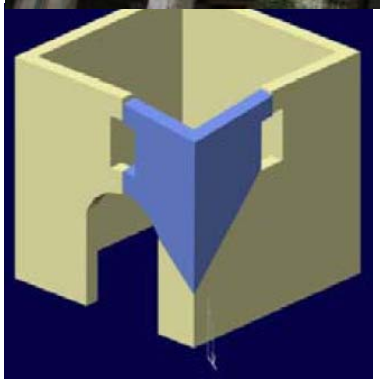
Damage to roof coverage

Damage:
- Overturning of the upper corner lateral wall;
- Partial collapse of the roof cover;



Overturning of the upper corner lateral wall



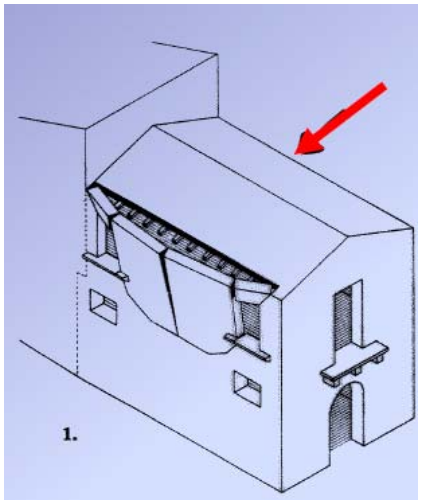


Damage to roof coverage

Damage:
- Local collapse of the lateral wall and the roof;

Mechanism:
- Overturning of the lateral wall;

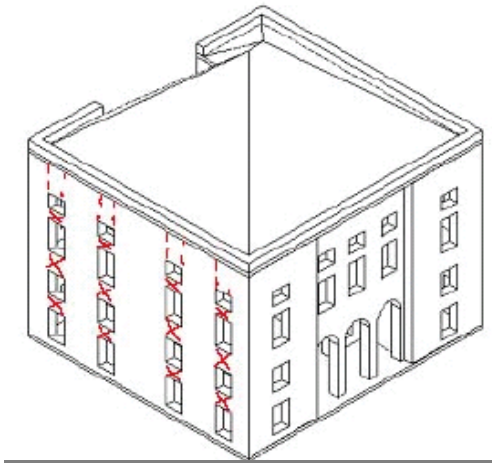
Structural causes:
- Poor connection between lateral walls and roof slab. The poor quality of masonry and presence of openings initiate the mechanism;

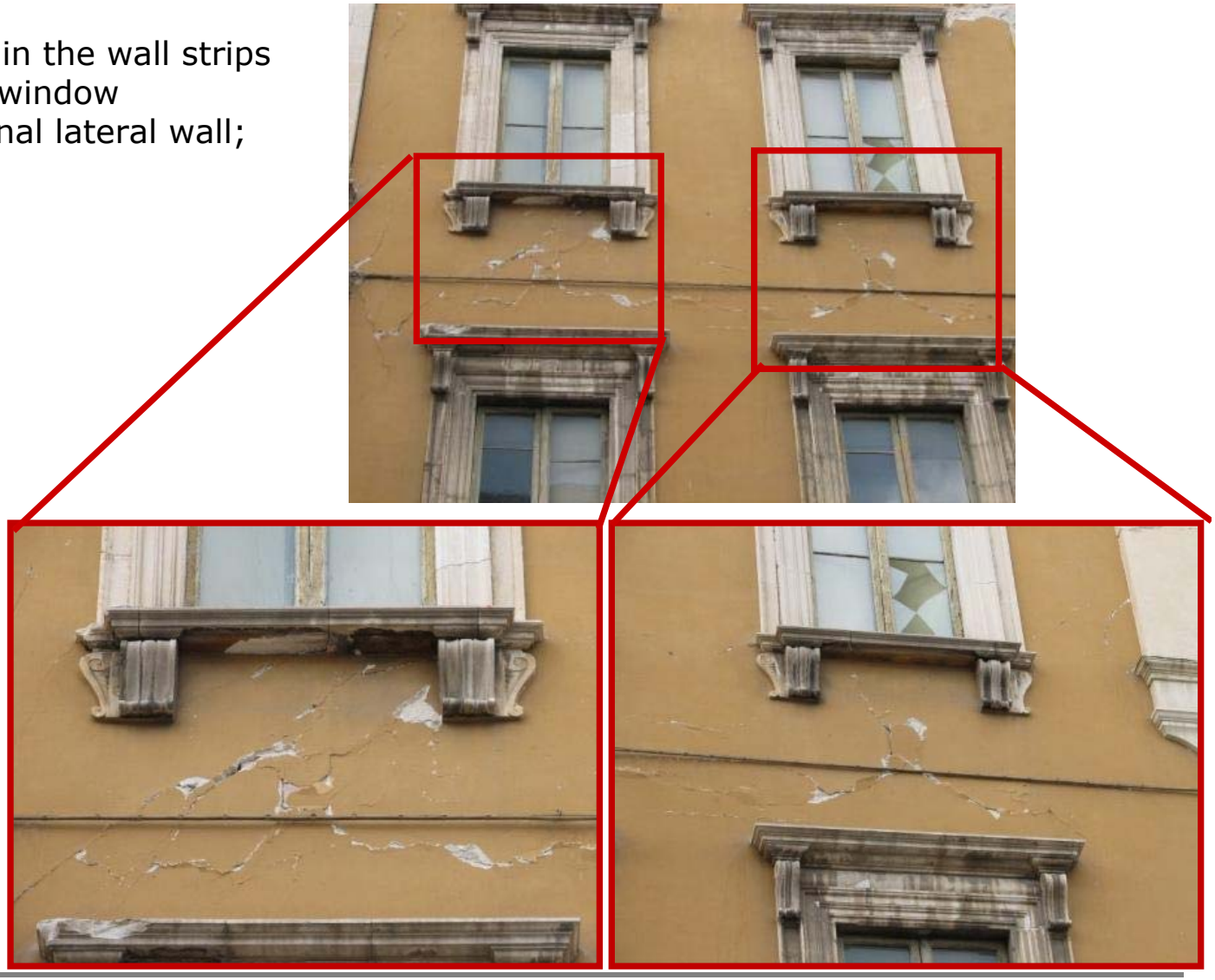


Damage in the wall strips

Damage:

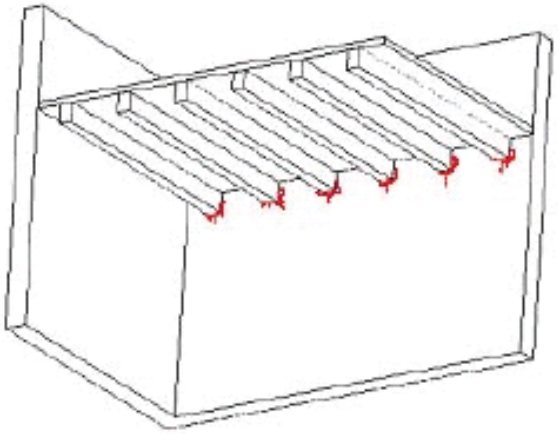
• typical cross cracks in the wall strips above and below the window openings of the external lateral wall;





Hammering of the floor beams

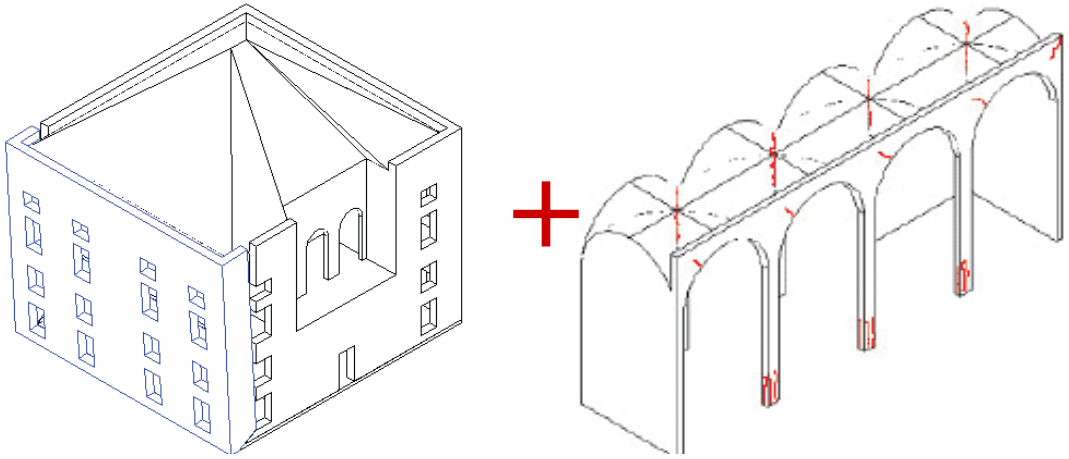
Damage:
• local damage in correspondence of the wall strips in the facade;
Mechanism:
• damage to the front facade, due to the hammering of the floor beams;
Structural causes:
• Floor slab not effectively connected to the wall masonry.



Damage to Arcades

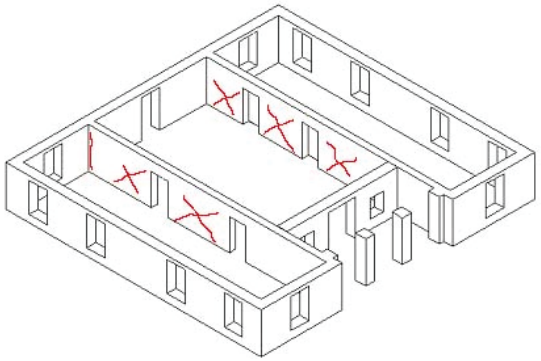
Damage:

•Overturning of the internal arcades "Loggiato" and of the columns;



Damage in the internal partition walls

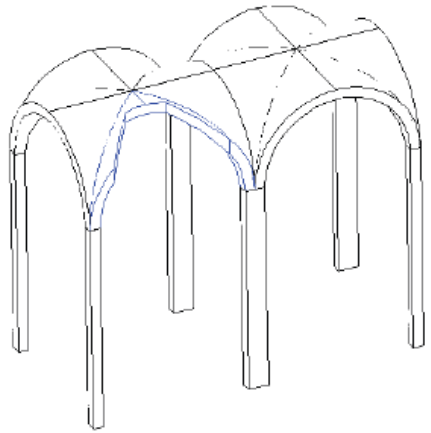
Damage in the internal walls



Damage in the stairs

Damage to roof ceilings

Collapse of the Vault



Damage of scaffolding system

Lucky!!

Biblioteca Provinciale, L'Aquila, (1877)

Damage:

- Severe overturning of the façade with signs of compressions on the column of the ground floor;
- Severe shear cracks on the strip and keep walls;
- The internal vaults in the stairs are seriously damaged;

Estimation of Economic losses:

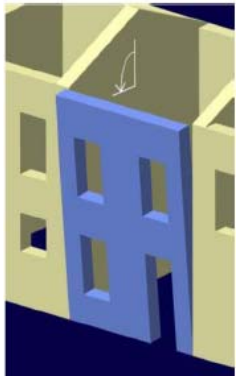
- 25.000.000 Euro;

Estimated Recovery time:

- 8 years;

Plan view of the complex block

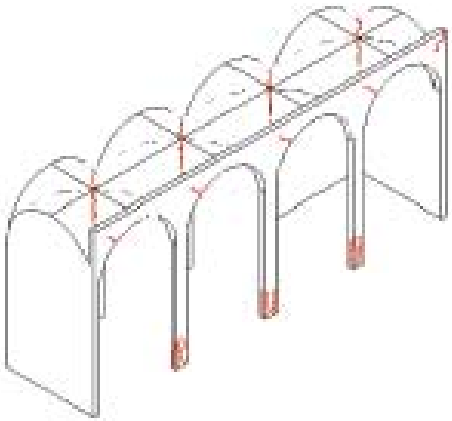
Overturning of the Facade



Compression in the columns of the facade

Damage:

•Compression damage to the columns of the arcade due to the overturning of the façade;

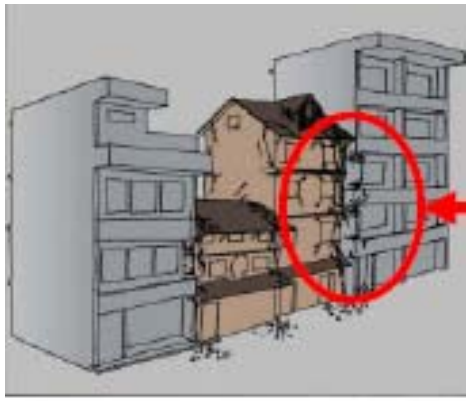


Composite overturning of the walls

Composite overturning of the walls (Shore-up Intervention)

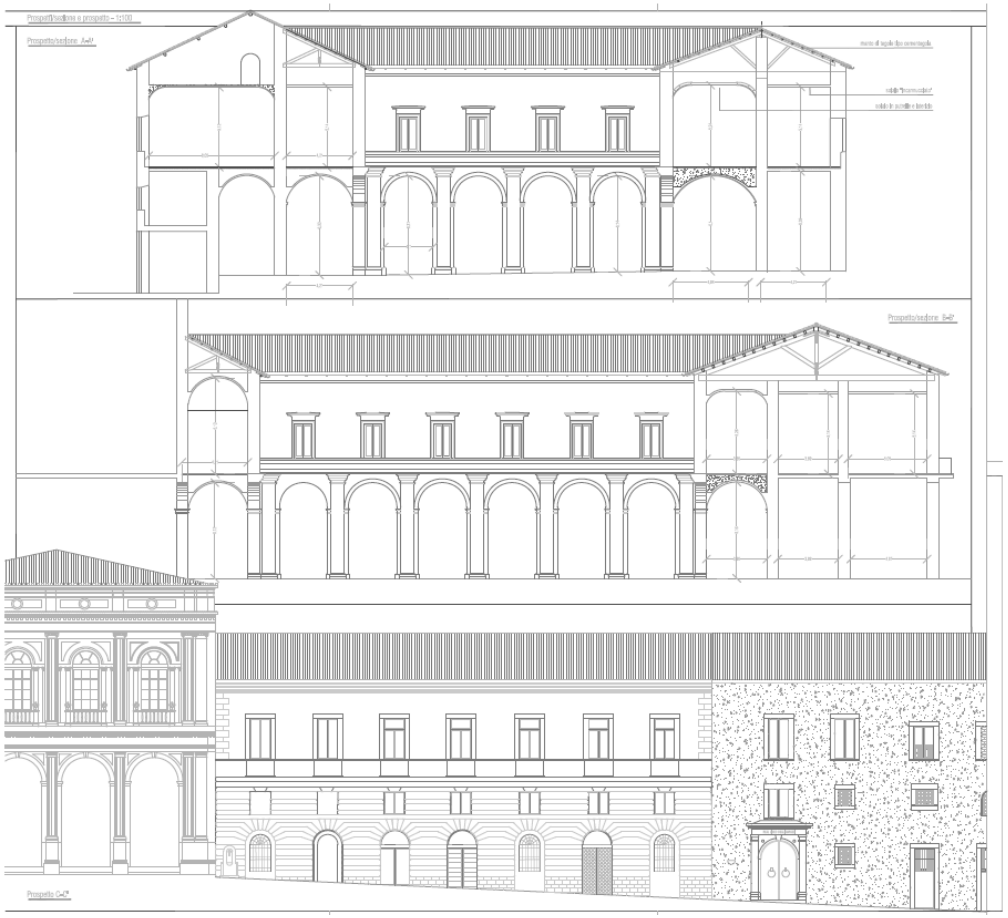
Damage to the library shelves

Pounding



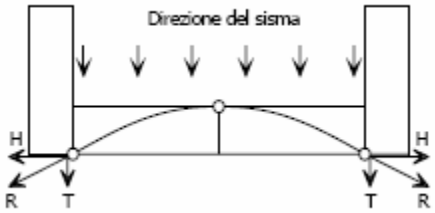
Convitto Nazionale

Front view and section of the main Yard



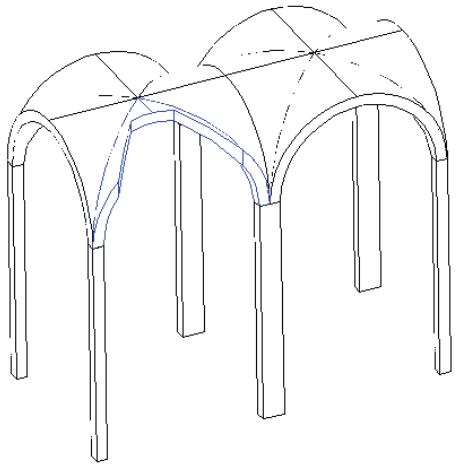
Horizontal flexure

Damage:
• local damage in the front façade wall with severe risk of collapse;
Mechanism:
• overturning due to lack of resistant to traction forces;
Structural causes:
• hammering of the roof beams on top of the lateral wall.

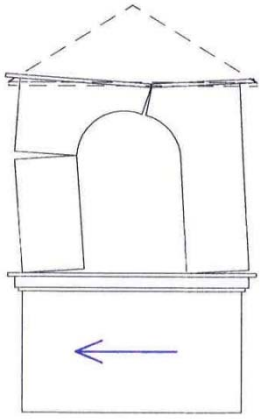


Total collapse of the vaults of the arcades

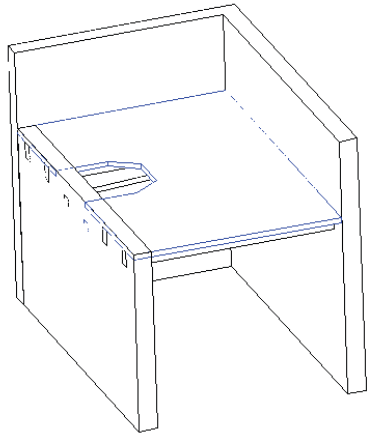
Damage:
• local collapse of the cross vaults of the arcades of the main yard of the Convitto;
Mechanism:
• rotation of the supports;
Structural causes:
• poor construction of the masonry vaults.



Damage in the Tower Bell



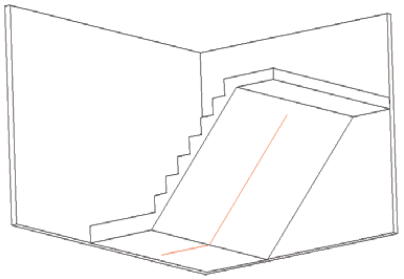
Collapse of the floor slab of the arcades

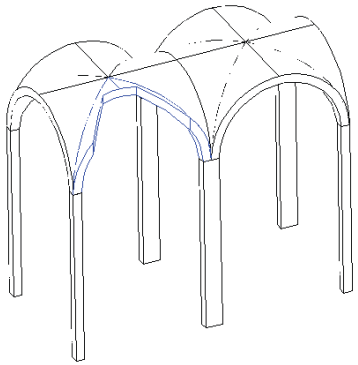


Overturning of the upper lateral wall

Safety of scaffolding system

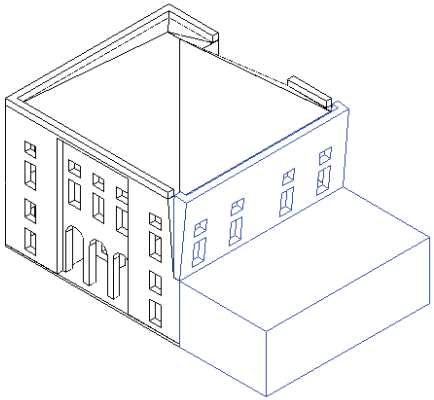
Cracks in the vaults of the stairs



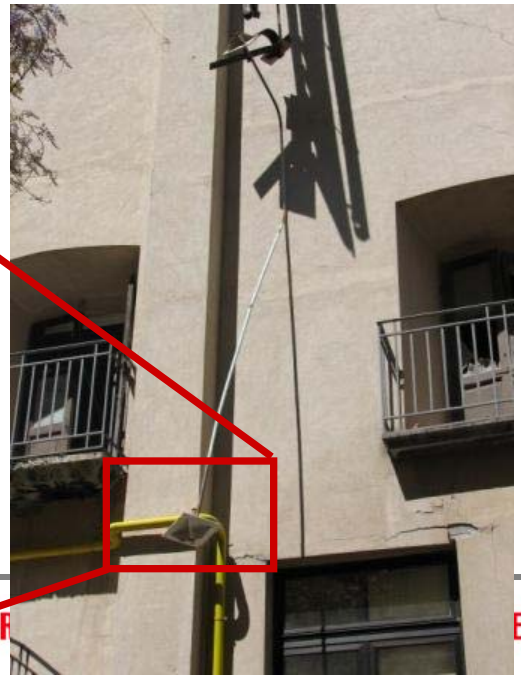


Damage for irregular shape

<u>Damage:</u>
• collapse of lateral wall and roof cover;
<u>Mechanism:</u>
• overturning due to poor connection between the roof and the lateral wall;
<u>Structural causes:</u>
• structural shape irregularities and poor masonry quality;



Total disconnection of cross-tie;



Damage to roof coverage

Damage in Paganica

3 foto di Onna Paganica e Castelnuovo

Damage in Onna

Shore-up intervention of a Church in Onna

Lucky again!!

Outline

- Seismic ground motion and fault mechanism;
- Italian seismic standard and the role of masonry in seismic zone;
- Damage to historical monuments;
- Damage to critical facilities;
- Damage to industrial buildings;
- Damage to lifelines;
- Damage to RC buildings;

Non structural components

- Most of the essential facilities (e.g hospitals, etc.) were not useful because of damage to non-structural components;

- Damage of nonstructural components also led to interruption of business activities;

- Wherever the stability of the building was not compromised damage to non structural components feared the population that were concerned going back in their houses;

San Salvatore Hospital

Damage to columns

Damage to columns

Poor quality of expansion joints

Damage to Suspended Ceilings system

Damage to internal infill walls

Outline

- Seismic ground motion and fault mechanism;
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- Damage to critical facilities;
- Damage to industrial buildings;
- Damage to lifelines;
- Damage to RC buildings;

Industrial Buildings

Industrial Buildings

Courtesy of O. Bursi

Industrial Silos in Bazzano

Courtesy of O. Bursi

Industrial Silos in Bazzano

Courtesy of O. Bursi

Outline

- Seismic ground motion and fault mechanism;
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- Damage to lifelines;
- Damage to RC buildings;

Road network

- ☐ Highway Teramo-L'Aquila interrupted
- ☐ Bridge closed

Bridge at Onna

- Bridge on the Aterno river

Geotechnical effects

Figure Convent Santa Maria di Collemaggio

Figure Road Monticchio to Onna

Partial collapse of shore lake

Figure Crack in the ground near the shore lake in San Demetrio dei Vestini

Outline

- Seismic ground motion and fault mechanism;
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- Damage to critical facilities;
- Damage to industrial buildings;
- Damage to lifelines;
- Damage to RC buildings;

Damage in L'Aquila (Pettino)

Shear wall concrete building

Disconnection joints

Shear walls

Three story reinforced concrete building

Three story reinforced concrete building

Three story reinforced concrete building

MCEER TEAM