CASE STUDY OF ANALYSIS AND INTERVENTION: TOMB OF DAVID AND CENACLE IN JERUSALEM

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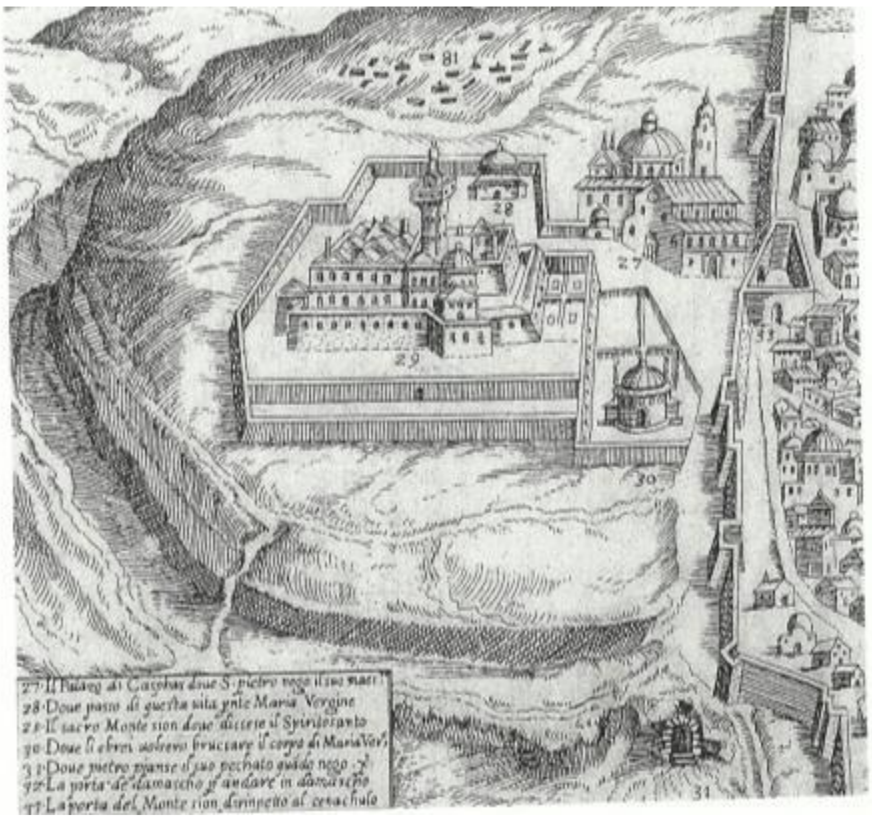
INGEGNERIA CIVILE, EDILE E AMBIENTALE
CIVIL, ARCHITECTURAL AND ENVIRONMENTAL ENGINEERING

INTRODUCTION

The main object is the **seismic analysis** and the structural assessment of a part of the monumental historical complex on Mount Zion, located at the south-west corner of the old city of Jerusalem, outside the walls. In particular the study is concentrated on the structural unit that contains the Tomb of David on the ground floor and the Room of the Last Supper (Cenacle) on the upper floor.

HISTORICAL NOTES

The historical buildings on Mount Zion were subjected to **several demolitions and reconstructions** over the centuries. Many structural and architectural transformations, starting from the I century, led to the definition of a complex building aggregate. Mount Zion was initially identified in the early traditions as the spot where once stood the City of David, in the west hills of Jerusalem

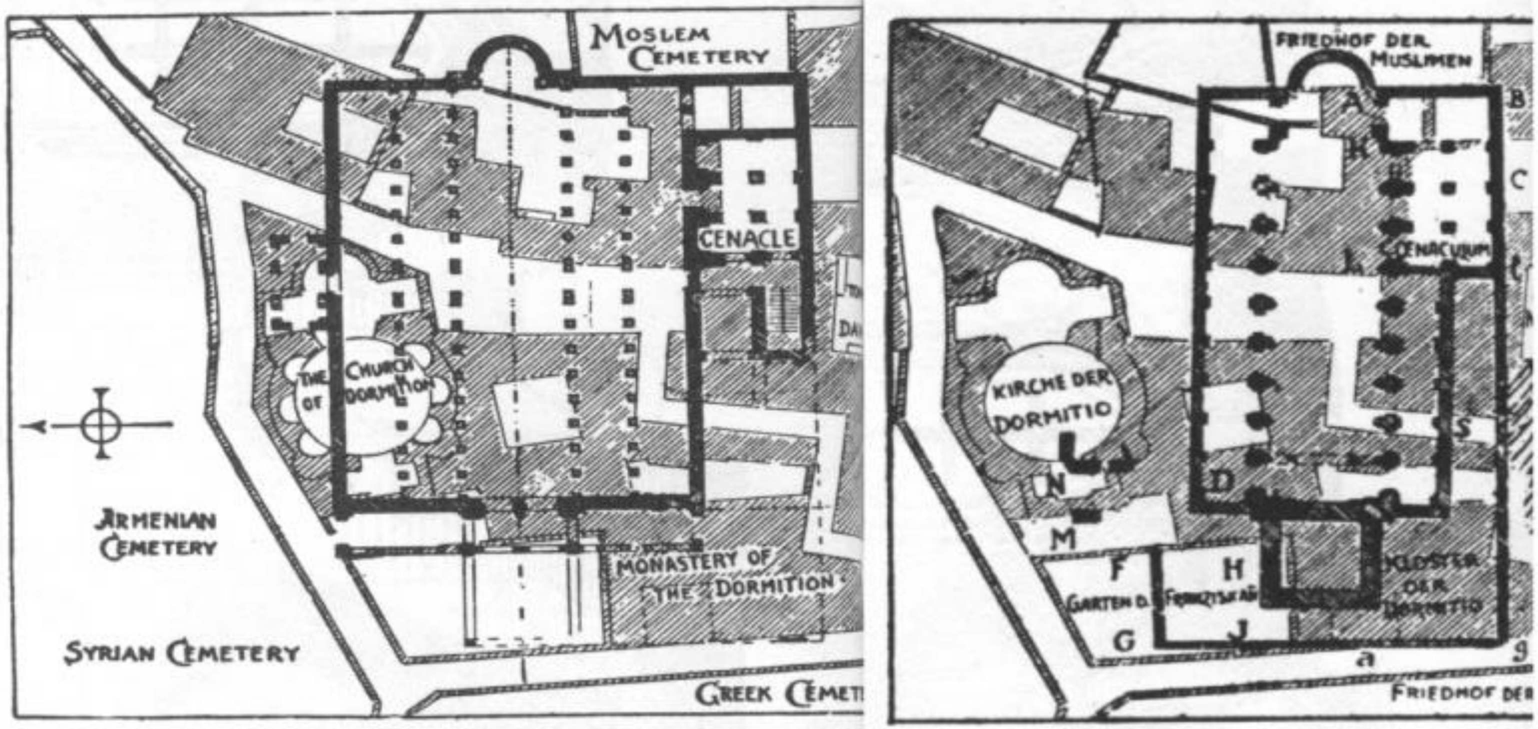


Detail of Mount Zion on the Jerusalem map of the friar Antonino d'Angioli, 1578

Map of Jerusalem by B. Amico, 1596: Jewish quarter and Monut Zion

HISTORICAL NOTES

The Cenacle hall is a **Crusader-Gothic** building from the 12th century. At that time, a church was built to commemorate "the Last Supper" and the Crusaders had reused parts of an earlier **Byzantine basilica** for its construction.



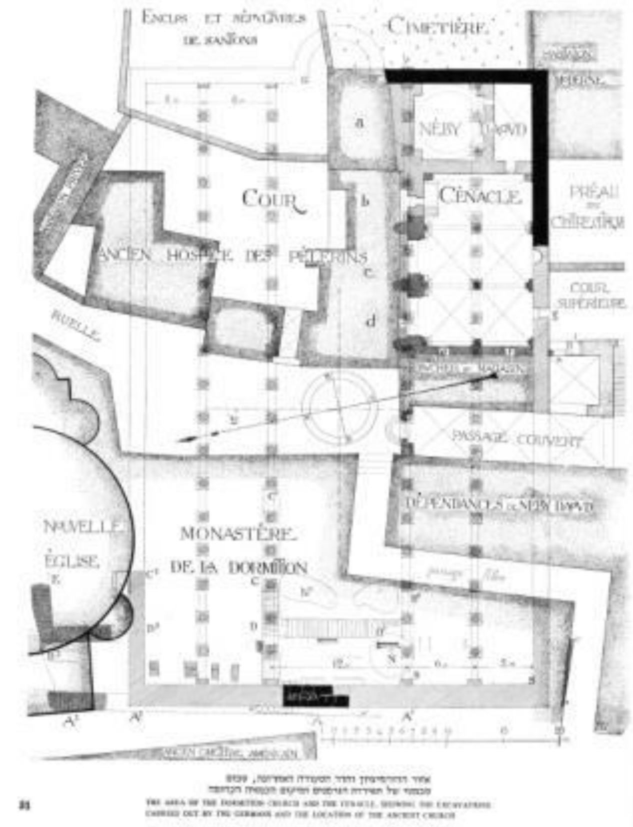
הכנסיה הביזאנטית בהר ציון
THE BYZANTINE CHURCH ON MOUNT ZION

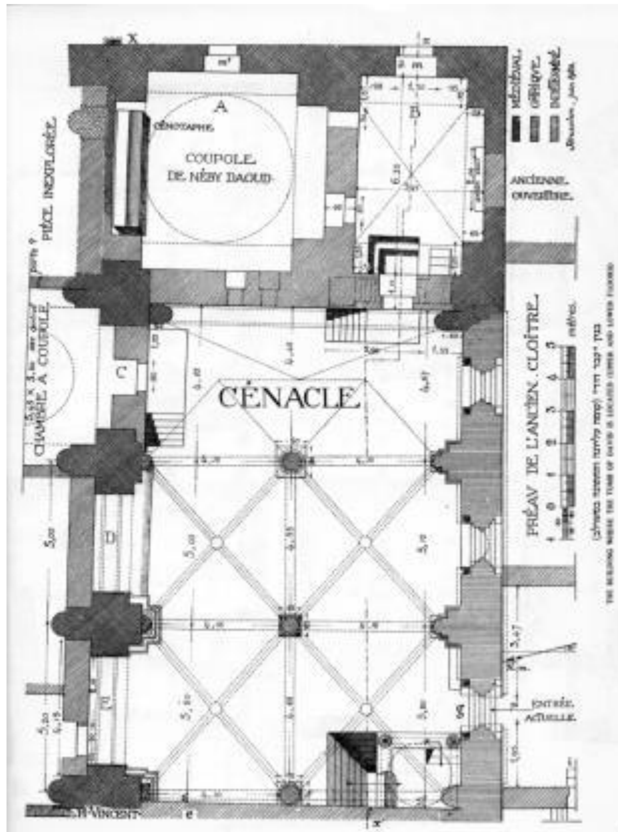
הכנסיה הצלבנית בהר ציון
THE CRUSADER'S CHURCH ON MOUNT

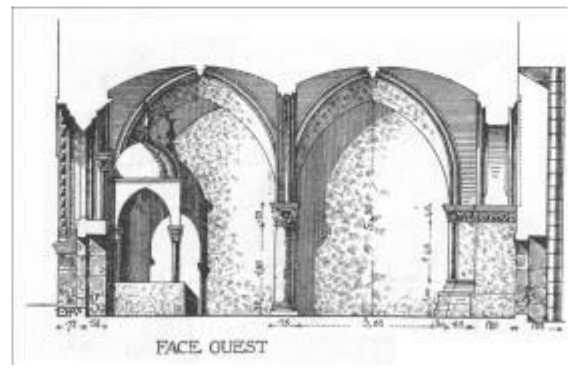
Recustruction of the bizantine (left) and crusaders (right) church

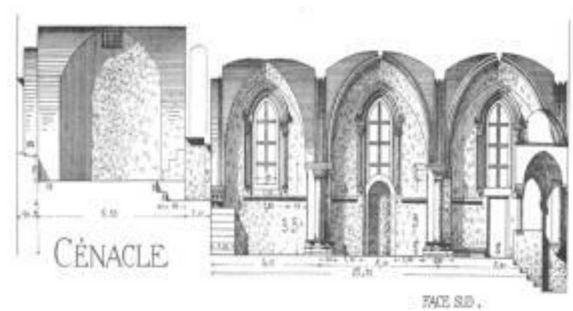
HISTORICAL NOTES

The sides of the crossed vaults above the halls were preserved, as well as the pillars, including the varied ornamentations above them and the massive piers. During the Mamluk period, the hall was turned into a mosque and at the end of the Ottoman period, a majestic mihrab that faced south toward Mecca was built.







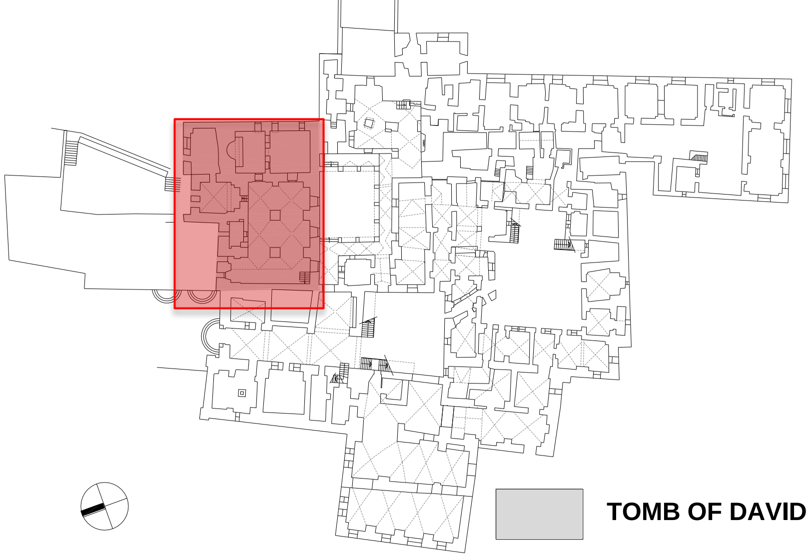


Plans and section of the french-german archeological survey

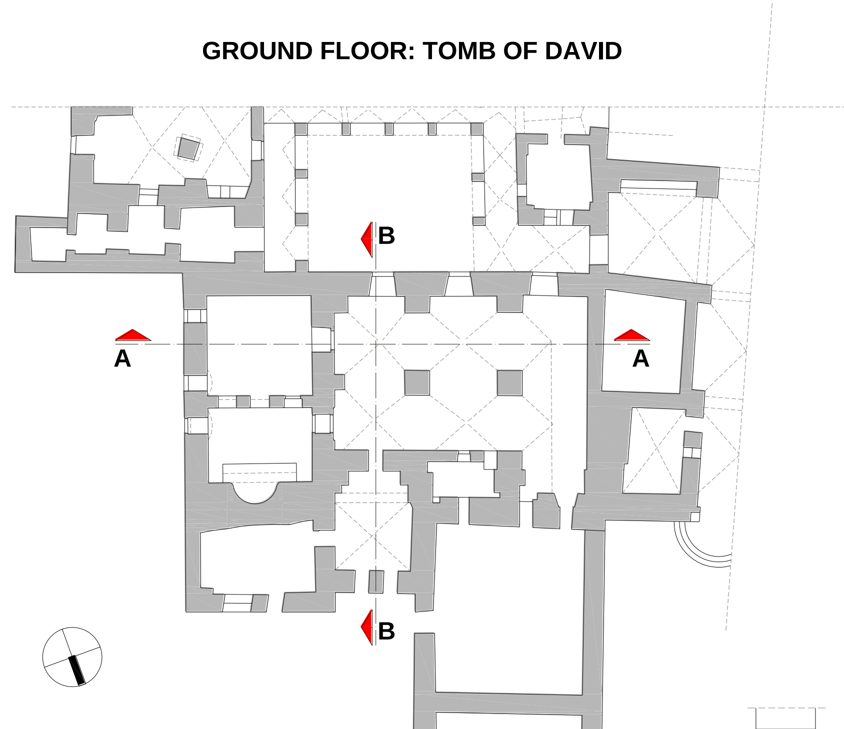
GEOMETRIC SURVEY

The **Tomb of David** is located on the ground floor with a system of groin vaults in the main entrance. The tomb is located in the eastern part of the floor and it is inserted in a room under a huge barrel vault.

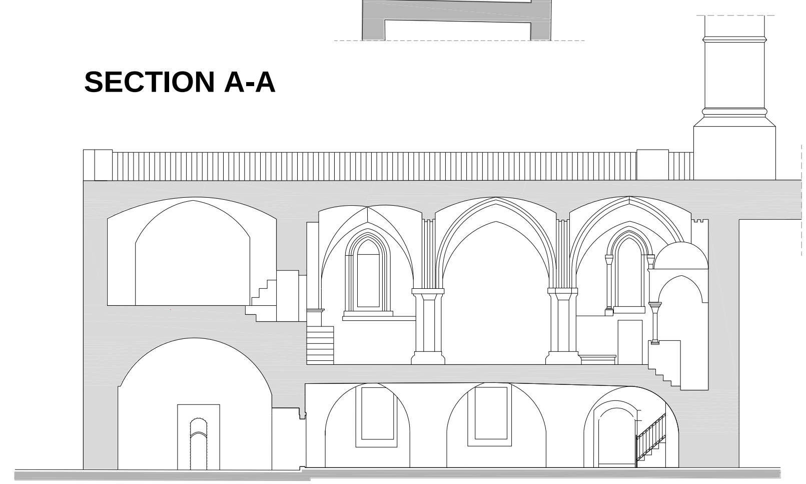
GROUND FLOOR



GROUND FLOOR: TOMB OF DAVID



SECTION A-A



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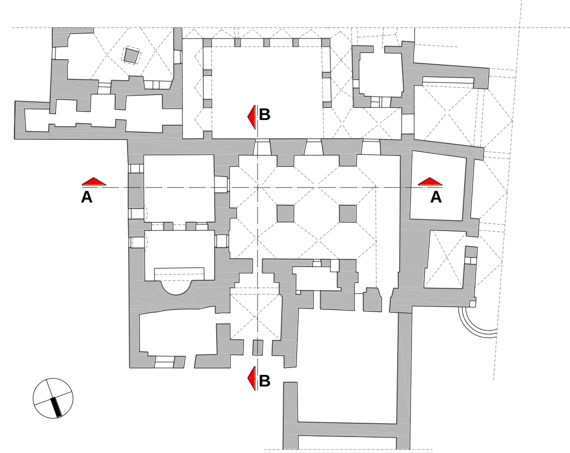
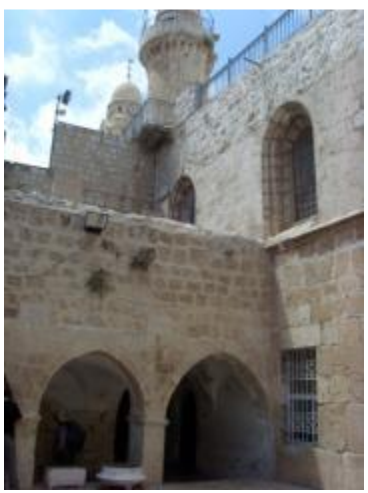
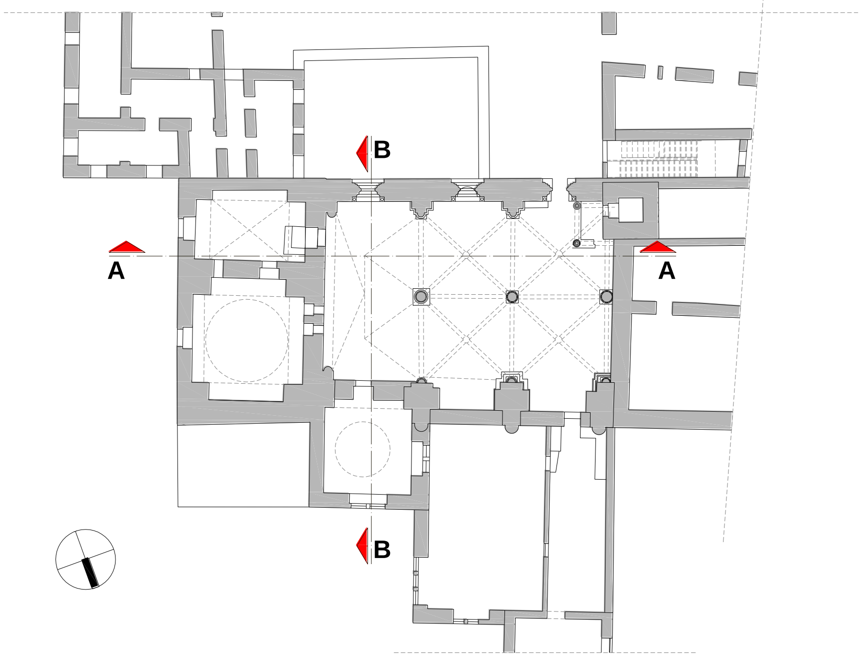




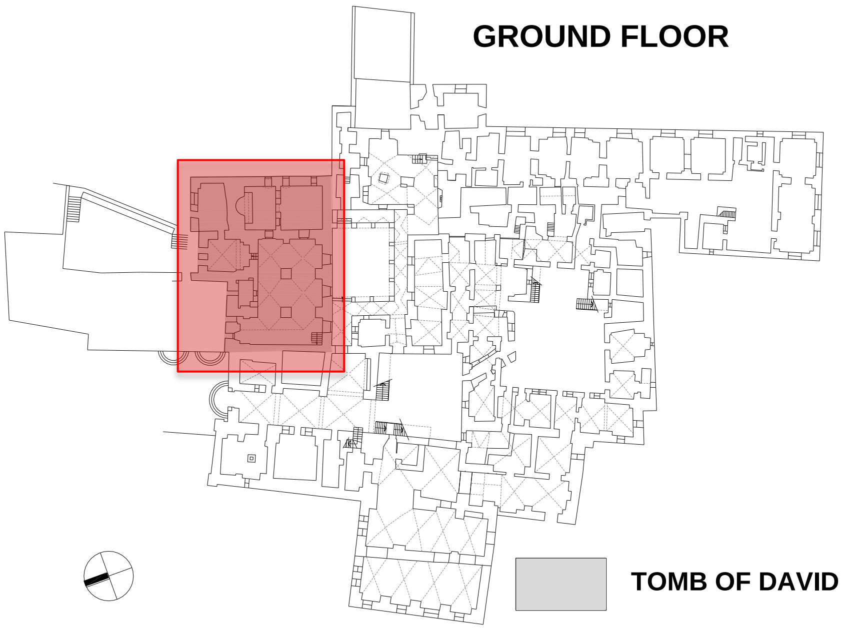
GEOMETRIC SURVEY

The **Room of the Last Supper** or **Cenacle** is located on the first floor. It has a system of rib vaults supported by the perimeter walls of the room and two pillars in middle of it.

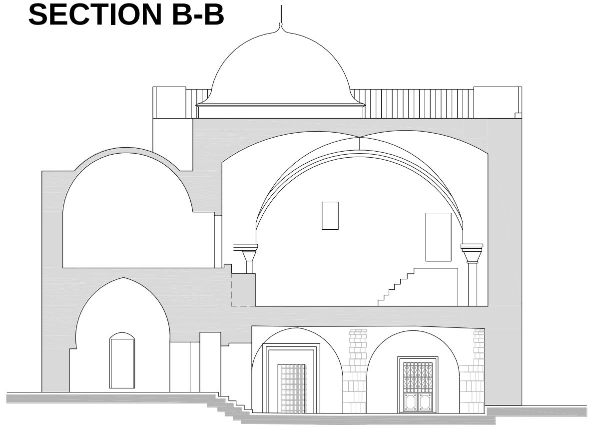
FIRST FLOOR: CENACULUM



GROUND FLOOR



SECTION B-B



GEOMETRIC SURVEY

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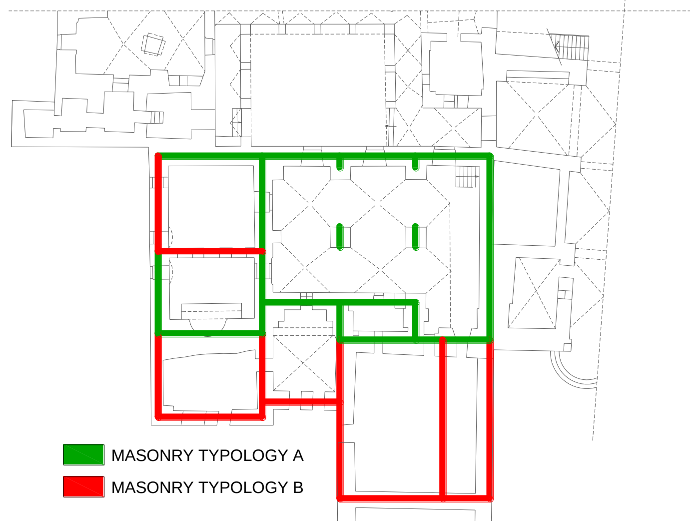
MATERIAL SURVEY - MECHANICAL PROPERTIES DEFINITION

The mechanical properties of stone masonry are derived from new **Italian Seismic code** (table C8A.2.1 of the Circolare 2 febbraio 2009, n. 617 C.S.LL.PP. “Istruzioni per l’applicazione delle «Nuove norme tecniche per le costruzioni»), which provides range of values for the principal mechanical parameters of different masonry typologies. After a detailed critical survey of the masonry walls and in situ inspections of the building it was possible to identify two different masonry typologies.

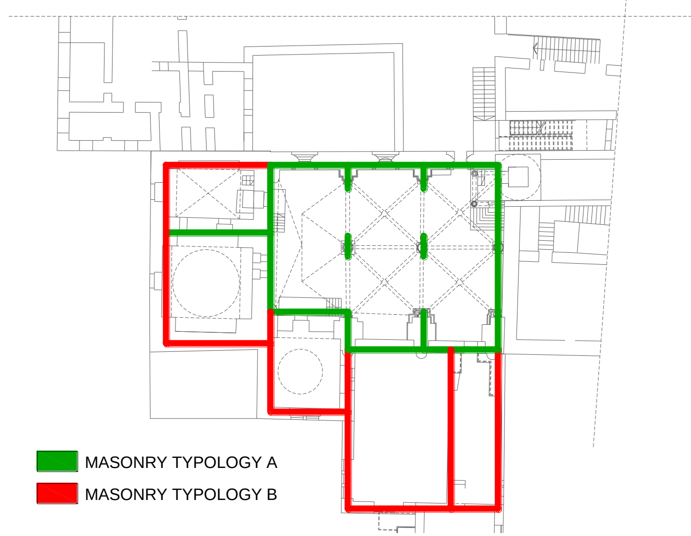
MECHANICAL PROPERTIES OF MASONRY [TAB. C8A.2.1]

MASONRY TYPOLOGY A	fm [N·cm^{-2}]		τ_0 [N·cm^{-2}]		E [N·mm^{-2}]		G [N·mm^{-2}]		w [kN·m^{-3}]
Squared blocks stone masonry with good texture	min	max	min	max	min	max	min	max	
	260	380	5,6	7,4	1500	1980	500	660	21
MASONRY TYPOLOGY B	fm [N·cm^{-2}]		τ_0 [N·cm^{-2}]		E [N·mm^{-2}]		G [N·mm^{-2}]		w [kN·m^{-3}]
Irregular stone masonry with inner core	min	max	min	max	min	max	min	max	
	200	300	3,5	5,1	1020	1440	340	480	20

GROUND FLOOR

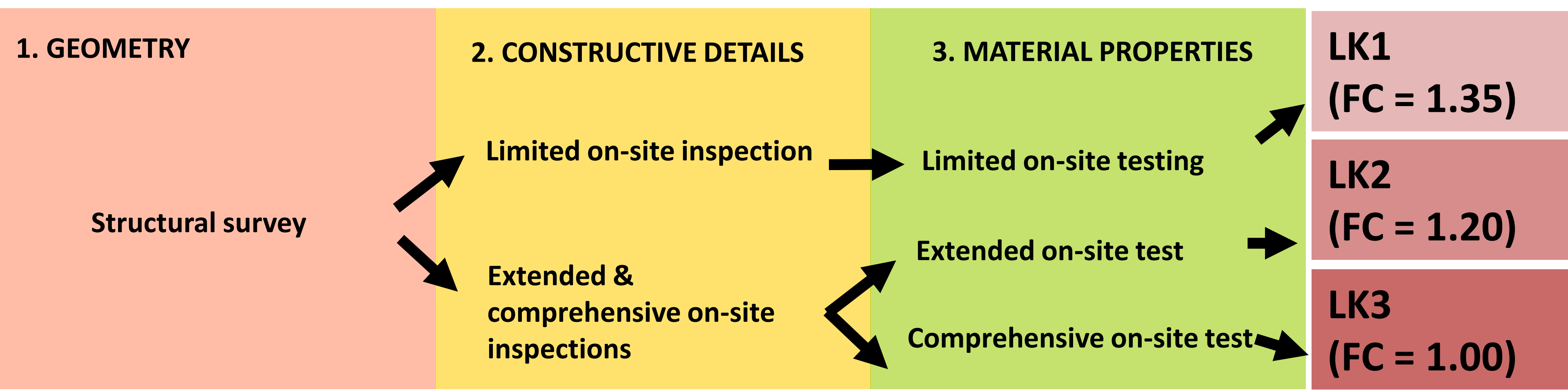


FIRST FLOOR



KNOWLEDGE LEVELS AND CONFIDENCE FACTORS

For existing buildings, Eurocode 8-3:2005, subsequently incorporated in the Circolare 2 febbraio 2009, n. 617 C.S.LL.PP. “Istruzioni per l’applicazione delle «Nuove norme tecniche per le costruzioni», establishes the determination of knowledge levels achieved by documentation and in situ inspections. Such values determine the method of analysis and the value of the confidence factor. In the present case the knowledge levels achieved is **KL1** with confidence factor **CF = 1.35**



$$f_{cd} = f_m / (FC \times \gamma_m)$$

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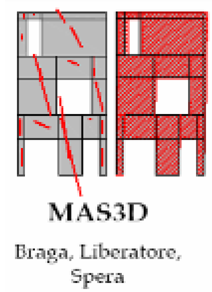
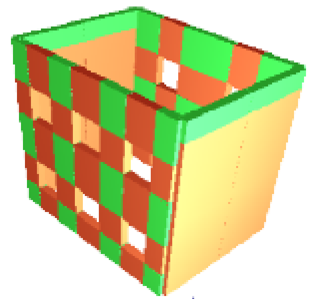
LEVELS OF KNOWLEDGE, RELATED METHODS OF ANALYSIS AND CONFIDENCE FACTORS [C8A.1.1]					
KNOWLEDGE LEVEL	GEOMETRY	DETAIL	MATERIALS	METHOD OF ANALYSIS	CONFIDENCE FACTOR CF
KL1	from original outline construction drawings with sample visual survey or from full survey	simulated design in accordance with relevant practice and from limited in-situ inspection	default values in accordance with standards of the time of construction and from limited in-situ testing	lateral force procedure, modal response spectrum analysis	1.35
KL2		from incomplete original detailed construction drawings with limited in-situ inspection or from extended in-situ inspection	from original design specification with limited in-situ testing or from extended in-situ testing	All	1.20
KL3		from original detailed construction drawings with limited in-situ inspection or from comprehensive in-situ inspection	from original test reports with limited in-situ testing or from comprehensive in-situ testing	All	1.00

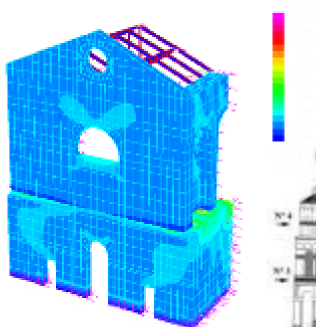
STRUCTURAL MODELLING AND SEISMIC ANALYSIS METHODS

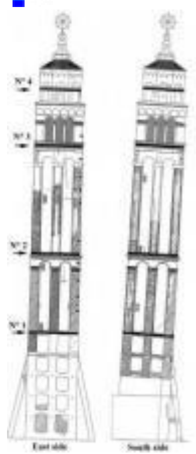
For existing masonry buildings it is possible to consider **various analysis methods**, according to the considered **appropriate model** which describe the structure and its seismic behaviour.
It is possible to consider:

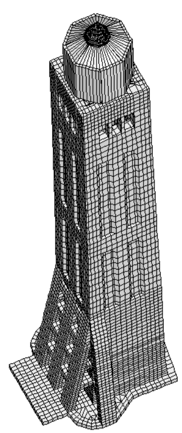
- **Macro-elements models**
- **Equivalent frame models**
- **Finite elements models**

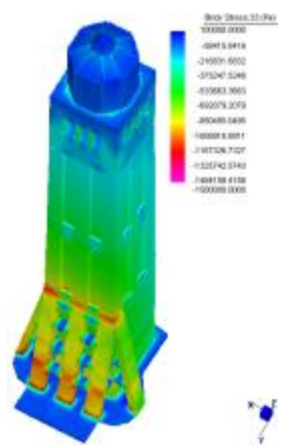


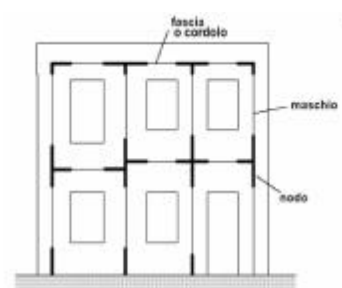


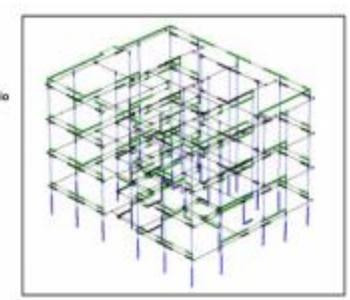










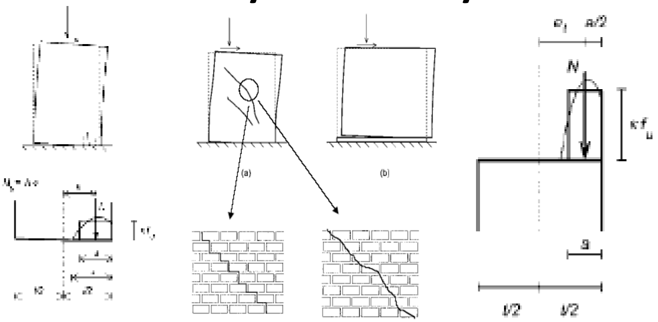


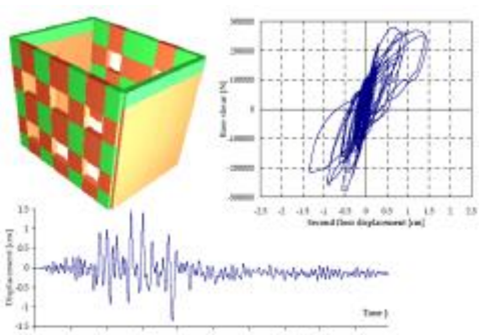
STRUCTURAL MODELLING AND SEISMIC ANALYSIS METHODS

In the case of cultural heritage buildings the assessment of the structure capacity and seismic safety must be considered at **local** and **global** level, using suitable analysis methods.

GLOBAL LEVEL:

- **linear static analysis**
- **modal dynamic analysis**
- **non linear static analysis**
- **non linear dynamic analysis**





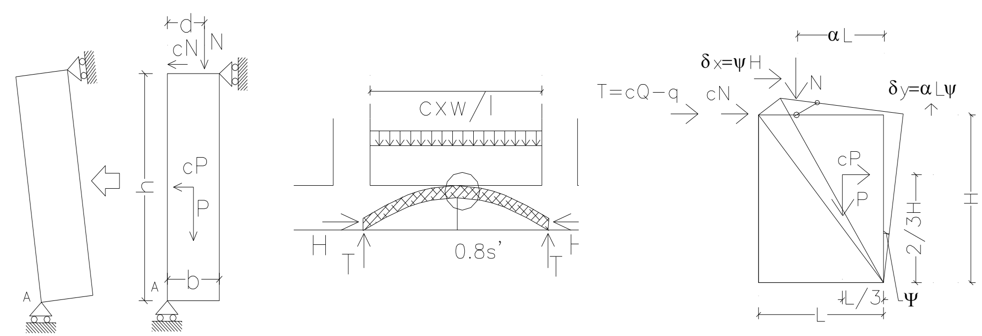
LOCAL LEVEL:

- **Simplified kinematic method**

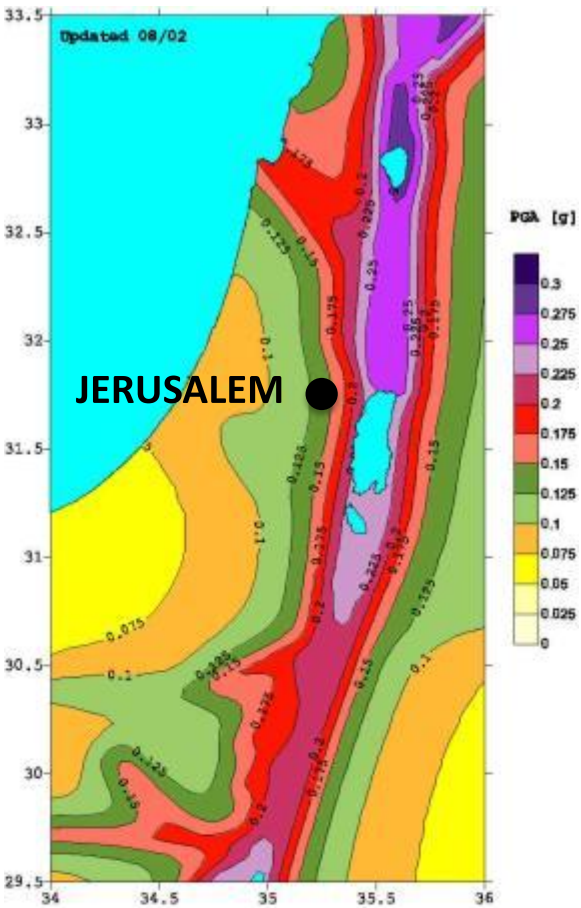
Out-of-plane (horizontal and vertical strips)

In-plane (kinematics chains)

These mechanisms are based on loss of equilibrium conditions and supply a **critical coefficient c = a/g** (inertial masses multiplier that activate the considered mechanism)

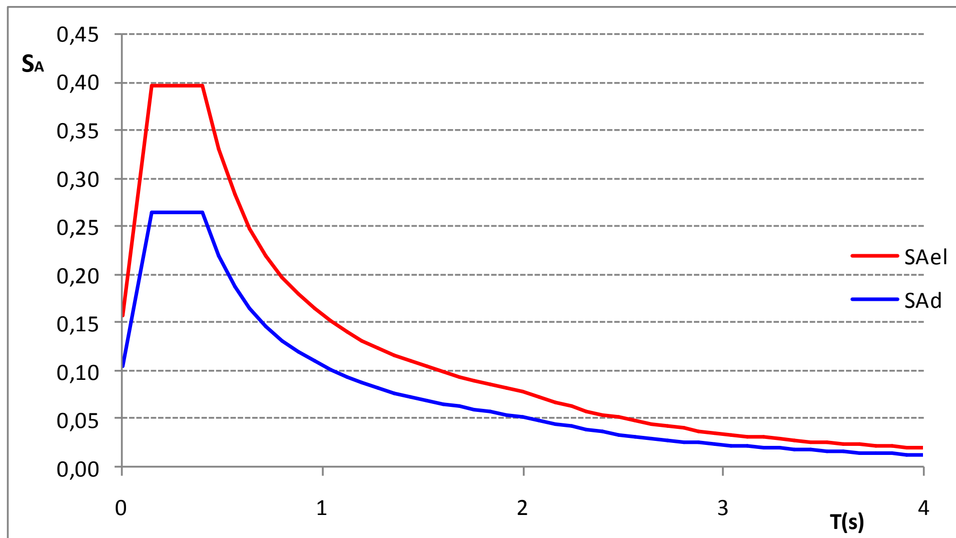


DEFINITION OF THE SEISMIC ACTION



	Peak ground acceleration a_{gR}	geographic coordinates	
		longitude	latitude
Jerusalem	0.132	35°12'E	31°47'N

PARAMETERS		VALUES
Ground Type	A	/
Reference peak ground acceleration on type A ground	a_{gR}	0.132 g
Soil Factor	S	1.00
Periods defining the elastic response spectrum	T_B	0.15 s
	T_C	0.4 s
	T_D	2.0 s
Importance Factor	γ_I	1.2
Behaviour Factor	q	1.5



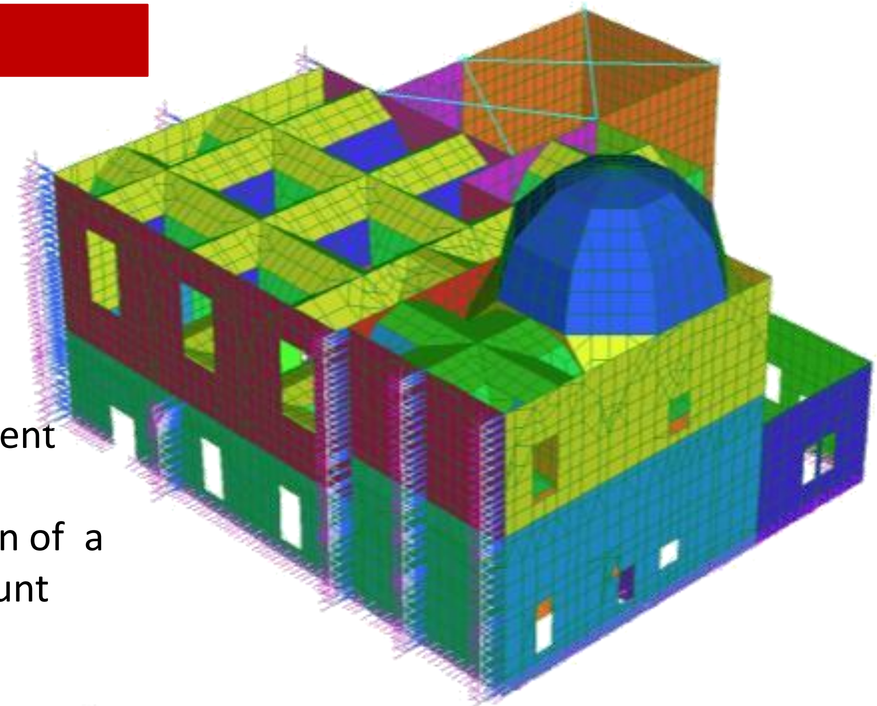
LINEAR MODAL ANALYSIS: FEM CONSTRUCTION

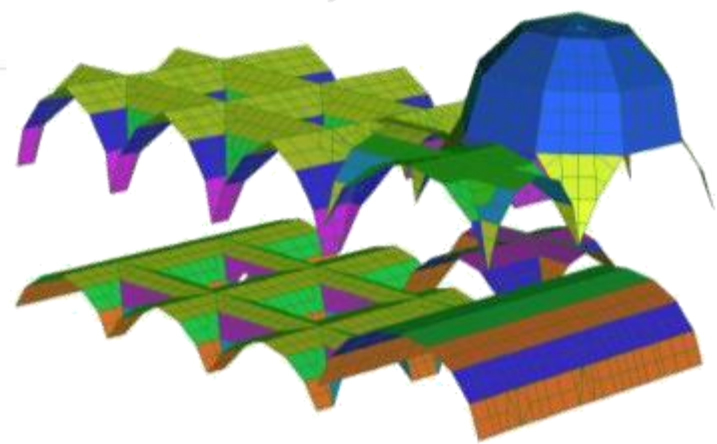
Software: **Straus7** FE Analysis System

- 26318 nodes;
- 273 beams;
- 8734 plates;
- 24 links;
- Fixed constraints at the base;

Spring elements placed in correspondence to the adjacent structural units;

Surface of the vault divided into three strips: application of a virtual material with fictitious density to take into account the different thickness of the infill material





LINEAR DYNAMIC MODAL ANALYSIS: LOAD ANALYSIS

Seismic load combination:

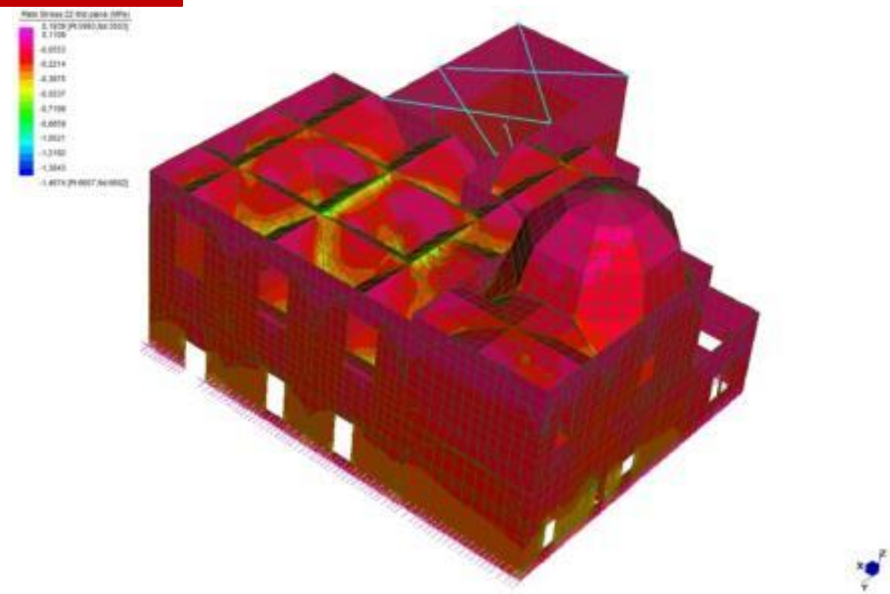
$$G_k + \sum_j \left(\psi_{2j} Q_{kj}\right)$$

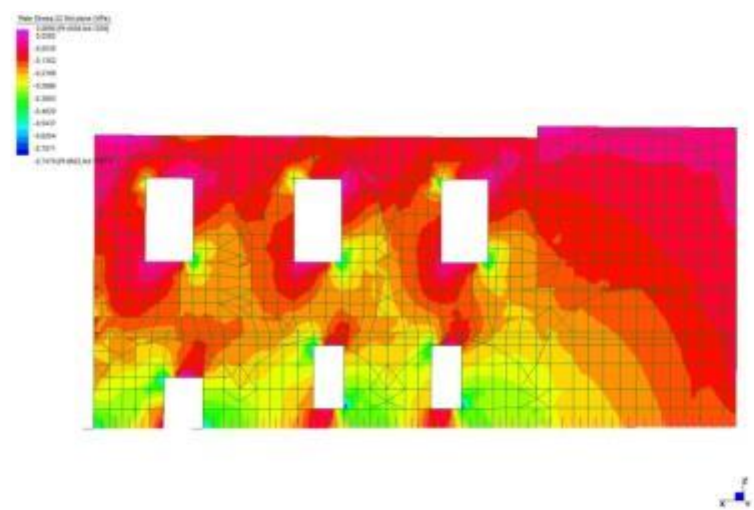
Gk = Dead loads

Qk = Live loads

COMBINATION COEFFICIENTS [NTC 2008]			
Category / Variable actions	ψ0j	ψ1j	ψ2j
Category C - Crowded buildings	0,7	0,7	0,6
Wind	0,6	0,2	0,0
Snow (altitude≤ 1000 m s.l.m.)	0,5	0,2	0,0

LIVE LOADS [NTC 2008]				
CATEGORY	AREAS	q_k [kN/m^2]	Q_k [kN]	H_k [kN/m]
C	Crowded areas			
	Cat C1 Hospitals, restaurants, cafes, banks, schools	3.00	2.00	1.00
	Cat C2 balconies, walkways, common stairs, meeting rooms, cinemas, theaters, churches, grandstands	4.00	4.00	2.00
	Cat C3 Areas without obstacles for the free movement of people, such as museums, exhibition halls, railway stations, dance halls, gymnasiums, free grandstands, buildings for public events, concert and sport halls	5.00	5.00	3.00

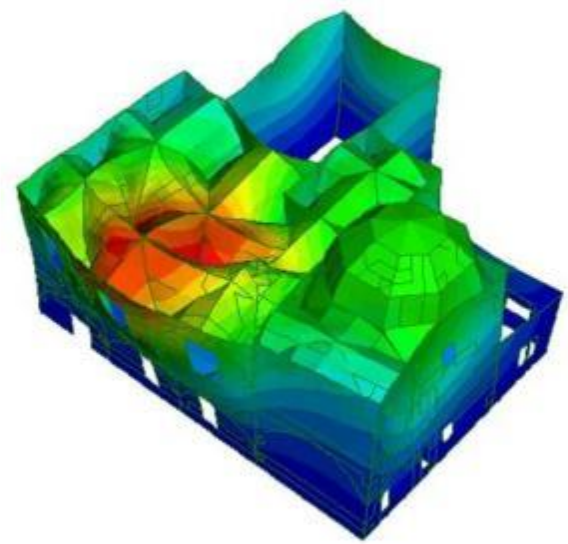




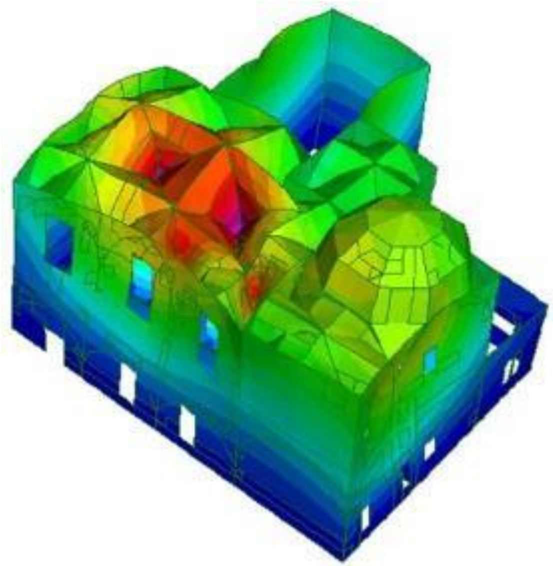
LINEAR DYNAMIC MODAL ANALYSIS: NATURAL FREQUENCY

Mode	Frequency [Hz]	Mass X [%]	Mass Y [%]	Mass Z [%]	Description
1	6,090	19,101	30,974	0,029	Global bending N-S
2	6,315	41,711	14,101	0,019	Global bending E-W
3	7,622	1,085	0,086	0,027	Global torsional
5	8,361	0,001	9,767	0,026	Global composite bending N-S
21	12,920	3,101	0,001	0,056	Local bending out of phase pillars E-W
26	13,920	0,060	5,245	0,373	Local bending in phase pillarsN-S
32	14,940	0,025	1,061	4,050	Local barrel vault South East
58	18,900	0,012	0,002	3,865	Local bending inner wall N-S

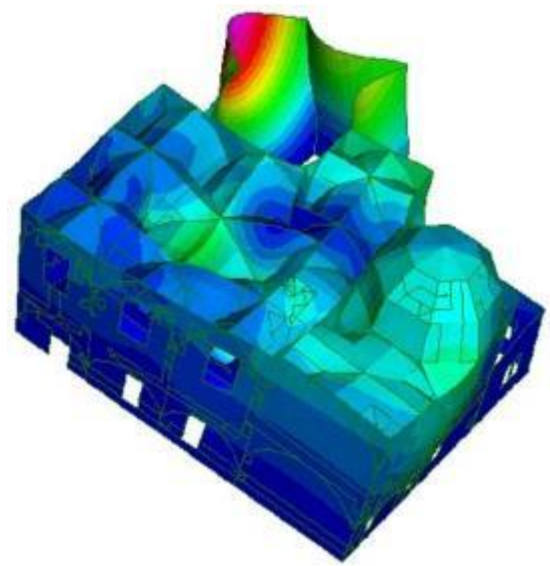
MODE 1: 6,09 Hz
GLOBAL BENDING N-S



MODE 2: 6,32 Hz
GLOBAL BENDING E-W



MODE 3: 7,62 Hz
GLOBAL TORSIONAL



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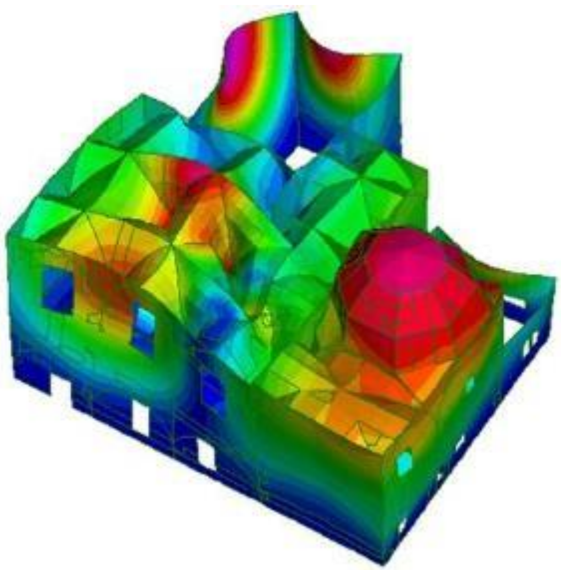
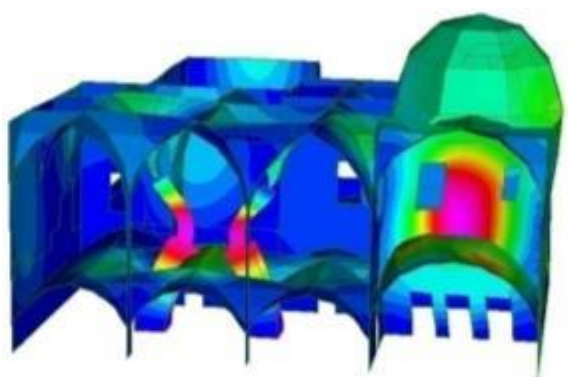
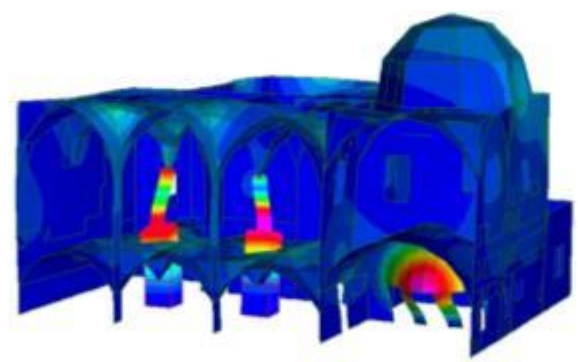
MODE 5: 8,36 Hz
Bending N-S



MODE 21: 12,92 Hz
Local mode of the pillars



MODE 58: 18,9 Hz
Local mode of the pillars



LINEAR DYNAMIC MODAL ANALYSIS: VERIFICATIONS

In plane bending and axial loading verification

$$M_u = \frac{l^2 t\,\sigma_0}{2}\left(1-\frac{\sigma_0}{0.85\cdot f_d}\right)$$

	COMBINATION	NOT VERIFIED MASONRY WALLS - GROUND&FIRST FLOOR					
		Masonry walls X direction		Masonry walls Y direction		Total	
X DIRECTION	Ex + 0,3Ey	2/40	5%	0/32	0%	2/72	**3%**
	Ex - 0,3Ey	0/40	0%	0/32	0%	0/72	0%
	-Ex + 0,3Ey	2/40	5%	0/32	0%	2/72	**3%**
	-Ex - 0,3Ey	0/40	0%	0/32	0%	0/72	0%
Y DIRECTION	0,3Ex + Ey	0/40	0%	1/32	3%	1/72	**1%**
	0,3Ex - Ey	0/40	0%	0/32	0%	0/72	0%
	-0,3Ex + Ey	0/40	0%	1/32	3%	1/72	1%
	-0,3Ex - Ey	0/40	0%	0/32	0%	0/72	**0%**

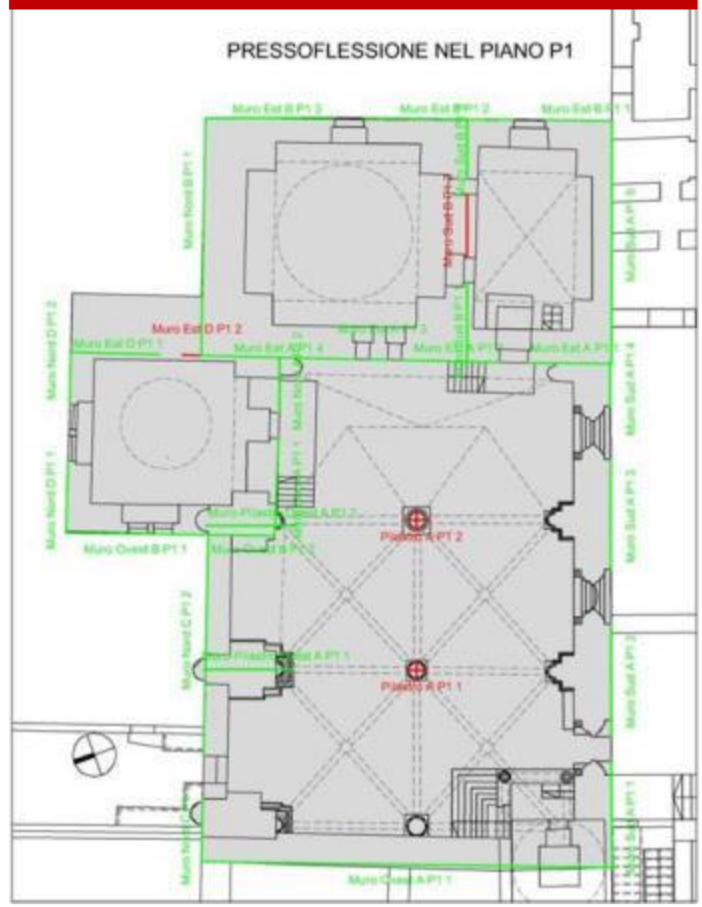
LINEAR DYNAMIC MODAL ANALYSIS: VERIFICATIONS

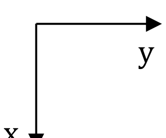
In plane bending and axial loading verification

$$M_u = \frac{l^2 t\, \sigma_0}{2}\left(1 - \frac{\sigma_0}{0.85 \cdot f_d}\right)$$

GROUND FLOOR

FIRST FLOOR





LINEAR DYNAMIC MODAL ANALYSIS: VERIFICATIONS

In plane shear verification

$$V_t = l \cdot t \cdot \frac{1.5\tau_{0_d}}{b} \cdot \sqrt{1 + \frac{\sigma_0}{1.5 \cdot \tau_{0_d}}}$$

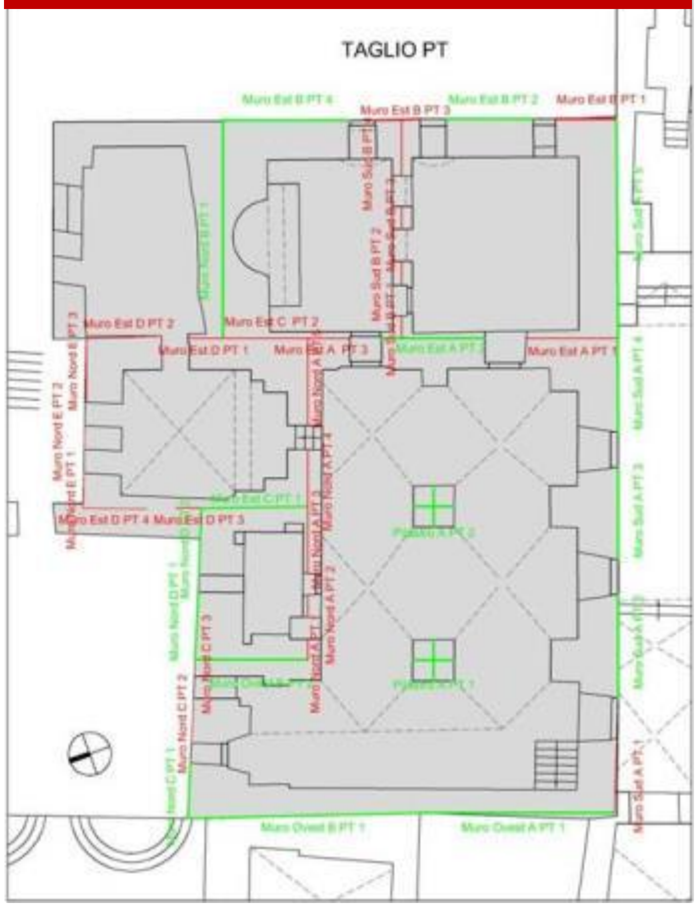
	COMBINATION	NOT VERIFIED MASONRY WALLS - GROUND&FIRST FLOOR					
		Masonry walls X direction		Masonry walls Y direction		Total	
X DIRECTION	Ex + 0,3Ey	27/40	67%	7/32	22%	34/72	47%
	Ex - 0,3Ey	21/40	52%	11/32	34%	32/72	44%
	-Ex + 0,3Ey	16/40	40%	9/32	28%	25/72	35%
	-Ex - 0,3Ey	22/40	55%	5/32	15%	27/72	37%
Y DIRECTION	0,3Ex + Ey	15/40	37%	9/32	28%	24/72	33%
	0,3Ex - Ey	4/40	10%	16/32	50%	20/72	28%
	-0,3Ex + Ey	7/40	17%	17/32	53%	24/72	33%
	-0,3Ex - Ey	13/40	32%	7/32	21%	20/72	28%

LINEAR DYNAMIC MODAL ANALYSIS: VERIFICATIONS

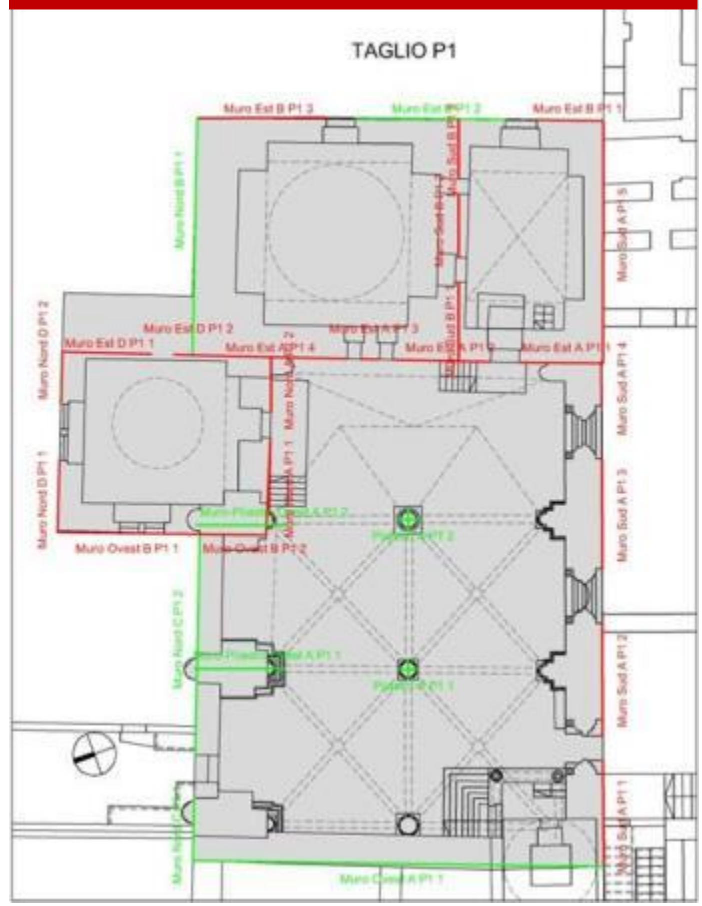
- In plane shear verification

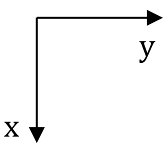
$$V_t = l \cdot t \cdot \frac{1.5\tau_{0_d}}{b} \cdot \sqrt{1 + \frac{\sigma_0}{1.5 \cdot \tau_{0_d}}}$$

GROUND FLOOR



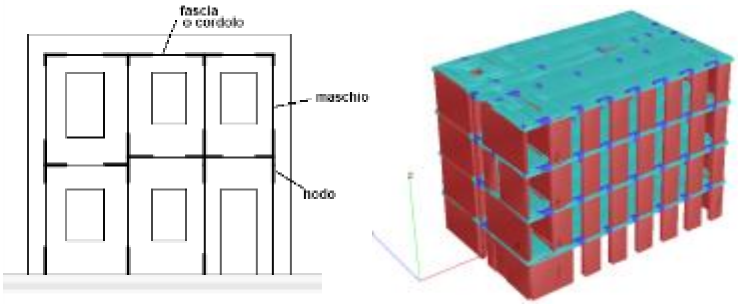
FIRST FLOOR



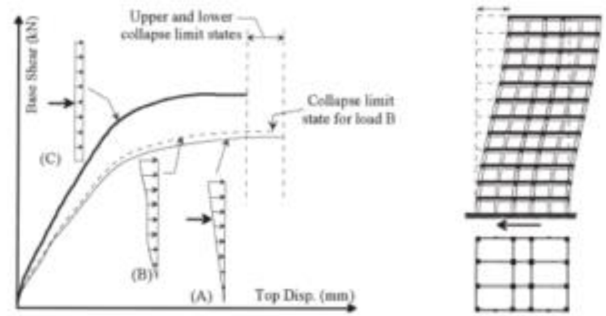


PUSHOVER ANALYSIS (NON LINEAR STATIC)

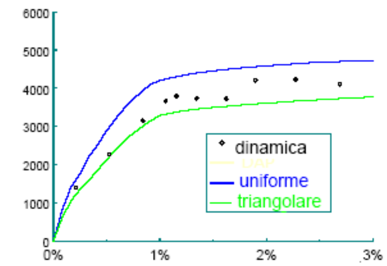
Equivalent frame model



Static distribution of seismic forces

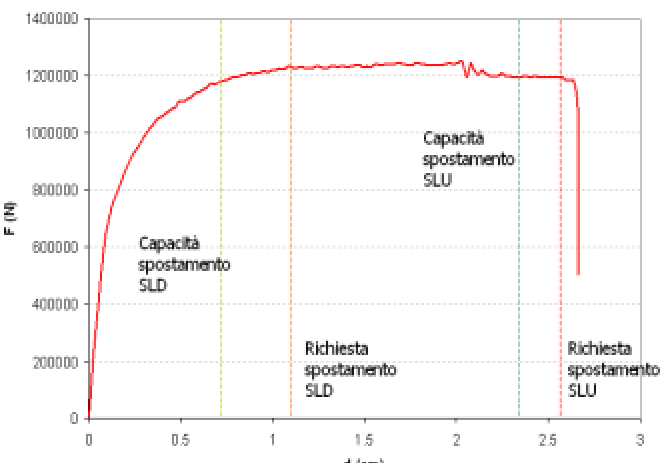


Capacity curves

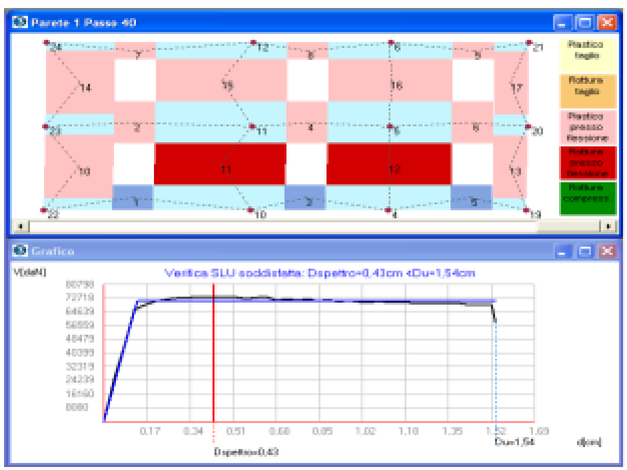


8-storey building with structural wall

Seismic verification → global level



Failure typology of masonry walls

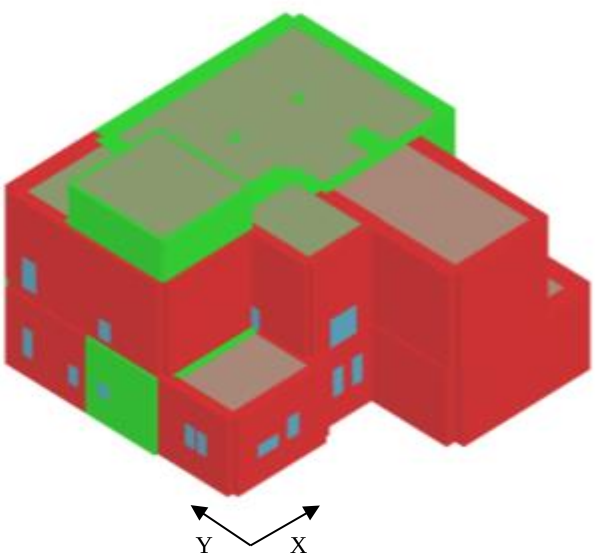


DISPLACEMENT CAPACITY > DISPLACEMENT DEMAND

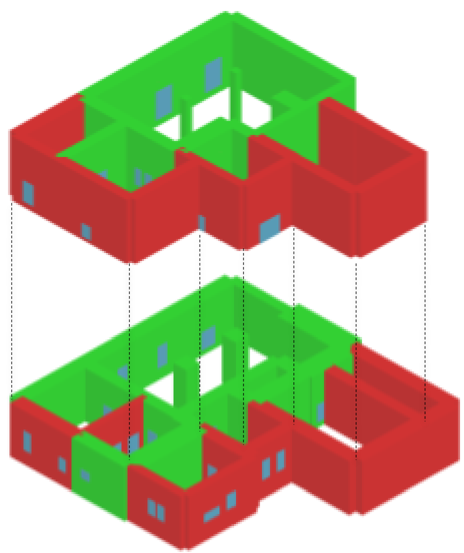
PUSHOVER ANALYSIS (NON LINEAR STATIC)

Simplified model built using 3MURI software:

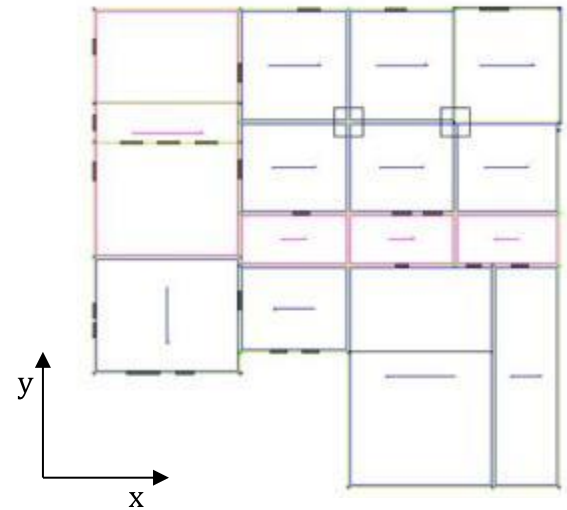
- 3-storey equivalent frame building: ground floor, first floor and dome;
- Vaulted system → rigid floor;
- No springs with the surrounding buildings/structures
- Caluculations performed according to the Italian Code (NTC 2008, not Eurocode 8).
- 2 types of horizontal loads: proportional to the mass and to the first mode shape along the principal directions



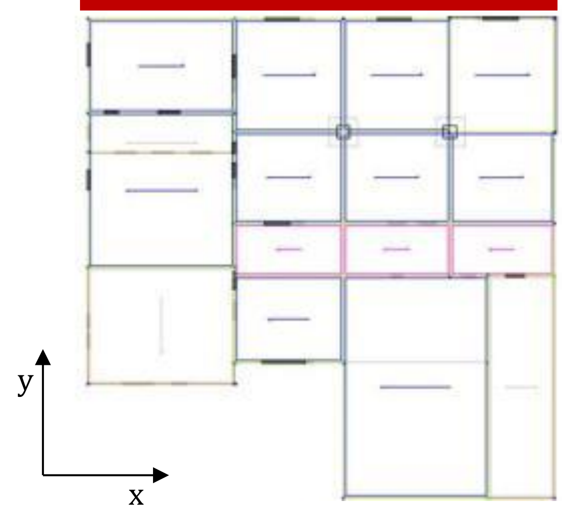
MASONRY TYPOLOGY



GROUND FLOOR



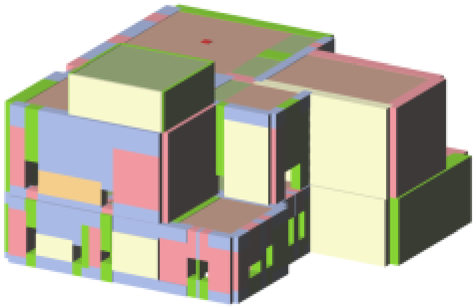
FIRST FLOOR

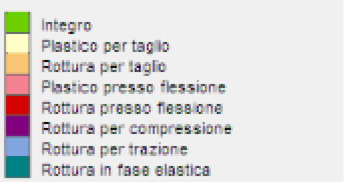


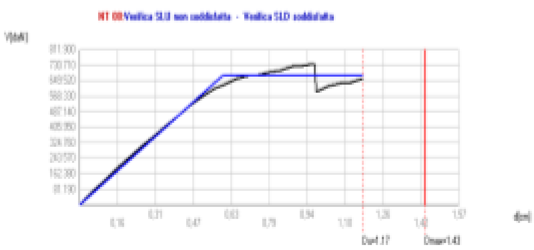
PUSHOVER ANALYSIS: VERIFICATIONS

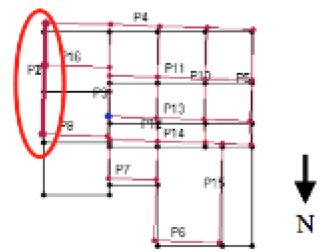
N.	Dir. sisma	Car. sismico prop.	Ecc. [cm]	DMax [cm]	Du [cm]	q* SLU	Alfa u	Ver.
1	+X	Masse	0,0	1,24	1,92	1,59	1,46	Sì
2	+X	1° modo	0,0	1,57	2,19	1,85	1,37	Sì
3	-X	Masse	0,0	1,34	3,13	1,60	1,87	Sì
4	-X	1° modo	0,0	1,71	2,86	2,17	1,38	Sì
5	+Y	Masse	0,0	1,16	1,51	1,60	1,25	Sì
6	+Y	1° modo	0,0	1,41	1,21	1,98	0,88	No
7	-Y	Masse	0,0	1,09	1,39	1,51	1,22	Sì
8	-Y	1° modo	0,0	1,36	1,22	2,02	0,91	No
9	+X	Masse	116,8	1,26	1,93	1,61	1,45	Sì
10	+X	Masse	-116,8	1,23	1,98	1,59	1,51	Sì
11	+X	1° modo	116,8	1,57	2,03	1,87	1,27	Sì
12	+X	1° modo	-116,8	1,52	2,11	1,87	1,36	Sì
13	-X	Masse	116,8	1,37	3,03	1,61	1,86	Sì
14	-X	Masse	-116,8	1,32	3,25	1,61	1,87	Sì
15	-X	1° modo	116,8	1,76	2,84	2,13	1,41	Sì
16	-X	1° modo	-116,8	1,70	2,06	2,09	1,20	Sì
17	+Y	Masse	113,5	1,14	1,64	1,56	1,36	Sì
18	+Y	Masse	-113,5	1,19	1,41	1,73	1,15	Sì
19	+Y	1° modo	113,5	1,39	1,25	1,90	0,91	No
20	+Y	1° modo	-113,5	1,43	1,17	2,13	0,84	No
21	-Y	Masse	113,5	1,07	1,52	1,50	1,33	Sì
22	-Y	Masse	-113,5	1,15	1,61	1,65	1,33	Sì
23	-Y	1° modo	113,5	1,35	1,34	1,90	1,00	No
24	-Y	1° modo	-113,5	1,38	1,14	2,15	0,84	No

EASTERN WALL

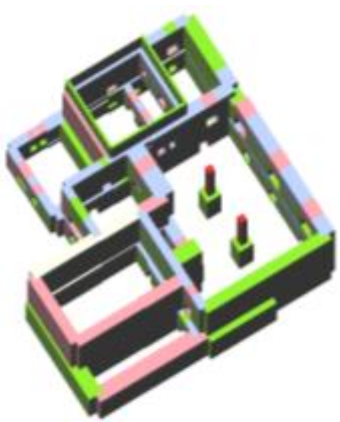


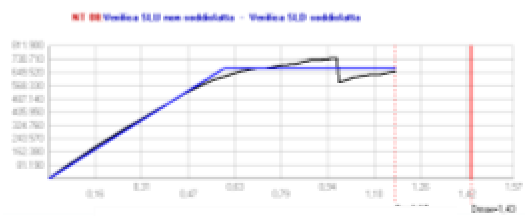


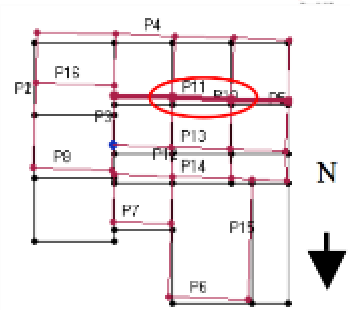




COLUMNS



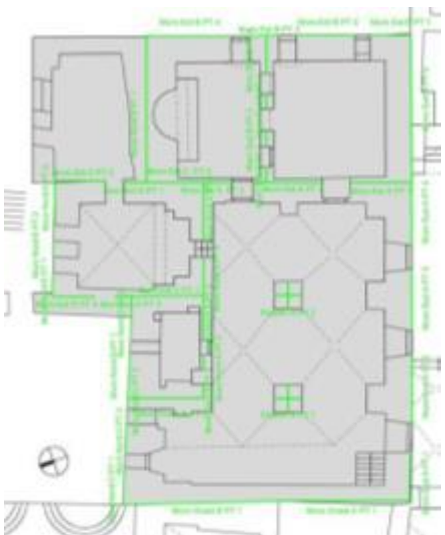




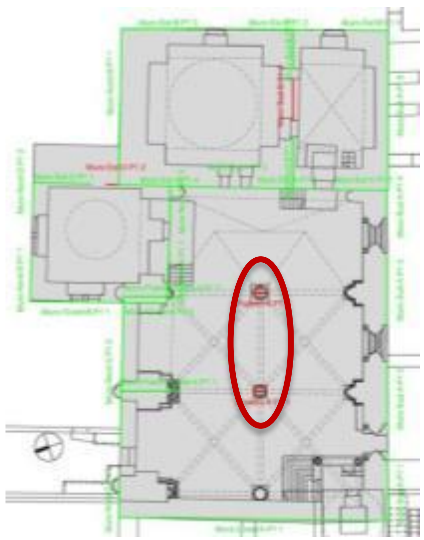
LINEAR DYNAMIC VS. PUSHOVER ANALYSES

- In plane bending and axial loading verifications

LINEAR DYNAMIC ANALYSIS



GROUND FLOOR



FIRST FLOOR

PUSHOVER ANALYSIS

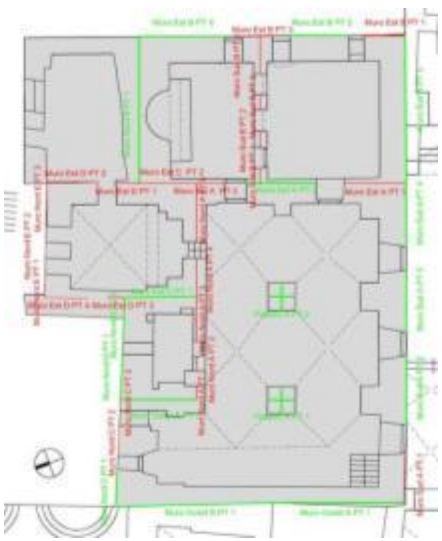
GROUND FLOOR

FIRST FLOOR

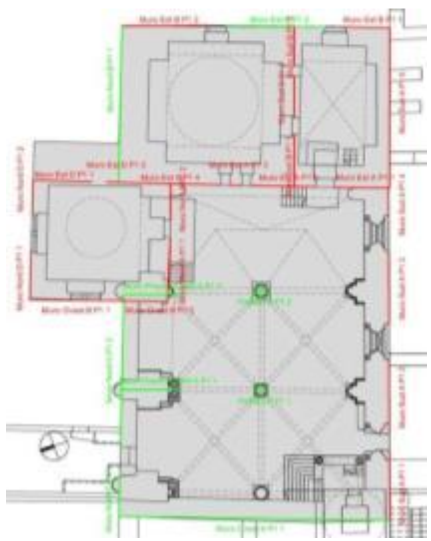
LINEAR DYNAMIC VS. PUSHOVER ANALYSES

- In plane shear verifications

LINEAR DYNAMIC ANALYSIS



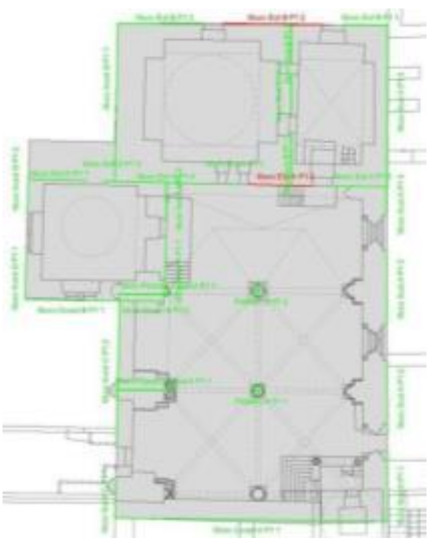
GROUND FLOOR



FIRST FLOOR

PUSHOVER ANALYSIS

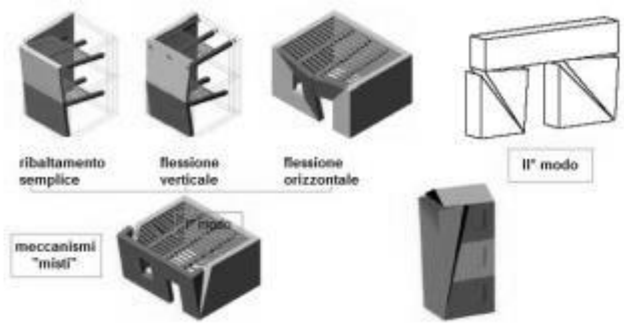
GROUND FLOOR

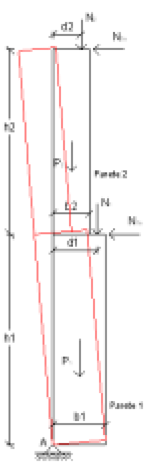


FIRST FLOOR

LIMIT ANALYSIS: LOCAL VERIFICATIONS

This method, proposed by the Italian code, is based on the failure mechanisms observed in masonry buildings after severe seismic events, and it is based on the evaluation of the limit analysis of masonry portions - considered as rigid blocks - subjected to their self weight (stabilising effect) and horizontal forces (earthquake actions).



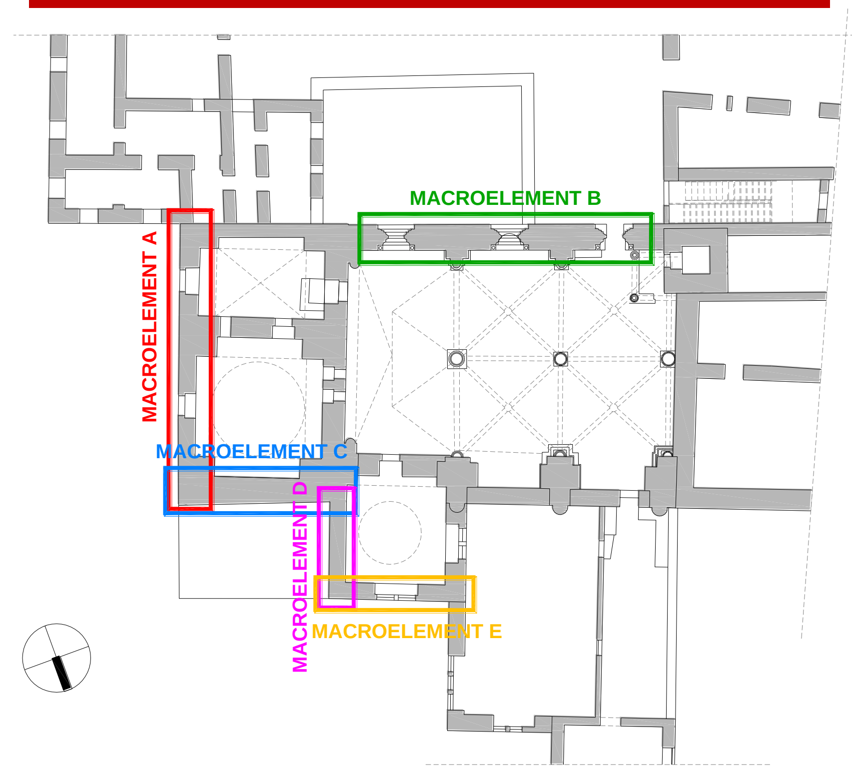


$$M_S = P_1\frac{b_1}{2} + N_1 d_1 + P_2\frac{b_2}{2} + N_2 d_2$$

$$M_R = c\cdot P_1\cdot\frac{h_1}{2} + c\cdot N_1\cdot h_1 + c\cdot P_2\left(h_1 + \frac{h_2}{2}\right) + c\cdot N_2\cdot h_{tot} + N_{1o}\cdot h_1 + N_{2o}\cdot h_{tot}$$

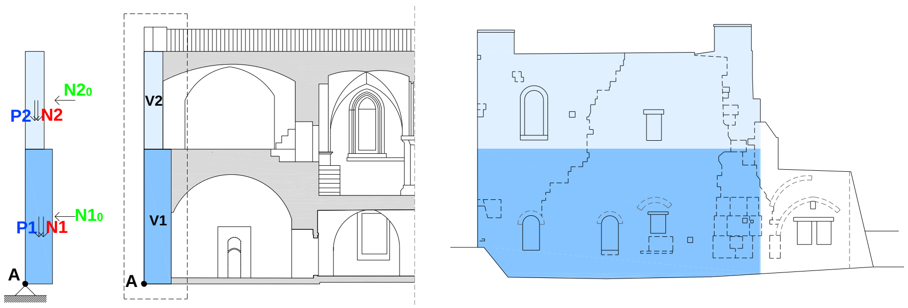
$$c = \frac{P_1\frac{b_1}{2} + N_1 d_1 + P_2\frac{b_2}{2} + N_2 d_2 - N_{1o} h_1 - N_{2o} h_{tot}}{P_1\frac{h_1}{2} + N_1 h_1 + P_2\left(h_1 + \frac{h_2}{2}\right) + N_2 h_{tot}}$$

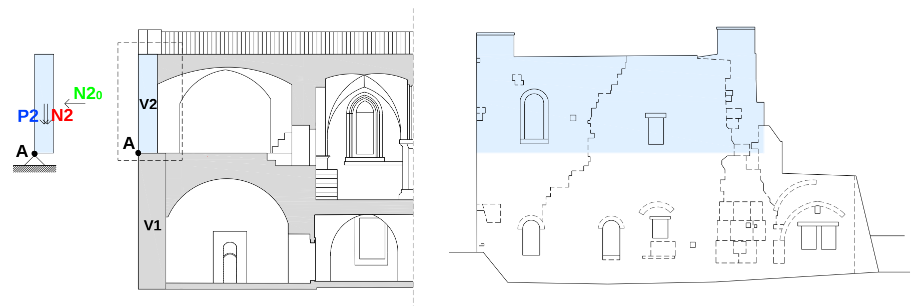
DEFINITION OF THE MACROELEMENTS



LIMIT ANALYSIS: LOCAL VERIFICATIONS

MACROELEMENT A → NOT VERIFIED!





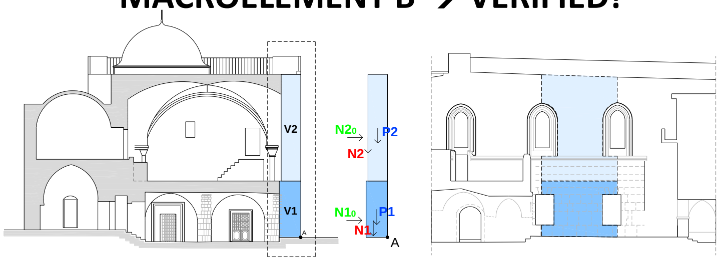
GLOBAL	LINEAR ANALYSIS								
	t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: [illegible]
	0,261	1922,03	26362,14	0,073	405,75	0,79	0,668	0,777	NO
	NON-LINEAR ANALYSIS								
	θ [rad]	d_{k0} [m]	d_0^* [m]	d_u^* [m]	d_s^* [m]	VERIFICATION: $d_u^* \geq d_s^*$ [m]			
	0,073	0,382	0,482	0,193	0,079	YES*			

PARTIAL	LINEAR ANALYSIS								
	t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: [illegible]
	0,093	171,35	4204,73	0,041	181,62	1,00	0,30	1,35	NO
	NON-LINEAR ANALYSIS								
	θ [rad]	d_{k0} [m]	d_0^* [m]	d_u^* [m]	d_s^* [m]	VERIFICATION: $d_u^* \geq d_s^*$ [m]			
	0,08	0,189	0,189	0,075	0,086	NO			

The analysis of the results indicates an overall lack of the *macroelement A* in relation to the seismic risk: it is necessary to proceed accordingly with the calculation and the design of retaining steel tie rods.

LIMIT ANALYSIS: LOCAL VERIFICATIONS

MACROELEMENT B → VERIFIED!

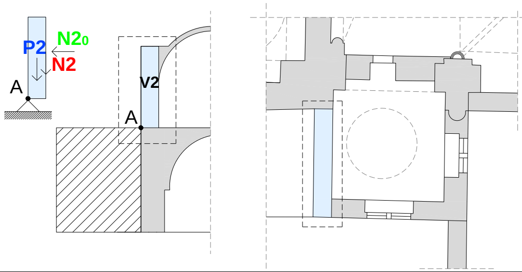


GLOBAL

LINEAR ANALYSIS								
t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: $a_0^* \geq a_0^*$
0,278	642,21	9365,58	0,069	143,99	0,73	0,685	0,777	NO

NON-LINEAR ANALYSIS					
θ [rad]	$d_{k,0}$ [m]	d_0^* [m]	d_u^* [m]	d_u^* [m]	VERIFICATION: $d_u^* \geq d_u^*$ [m]
0,067	0,392	0,387	0,155	0,079	YES

MACROELEMENT D → VERIFIED!

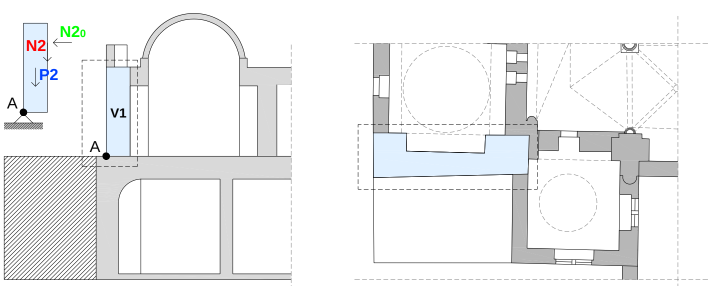


GLOBAL

LINEAR ANALYSIS								
t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: $a_0^* \geq a_0^*$
0,077	286,20	930,47	0,308	53,11	1,00	2,24	1,31	YES

NON-LINEAR ANALYSIS					
θ [rad]	$d_{k,0}$ [m]	d_0^* [m]	d_u^* [m]	d_u^* [m]	VERIFICATION: $d_u^* \geq d_u^*$ [m]
0,287	0,505	0,506	0,202	0,051	YES

MACROELEMENT C → VERIFIED!

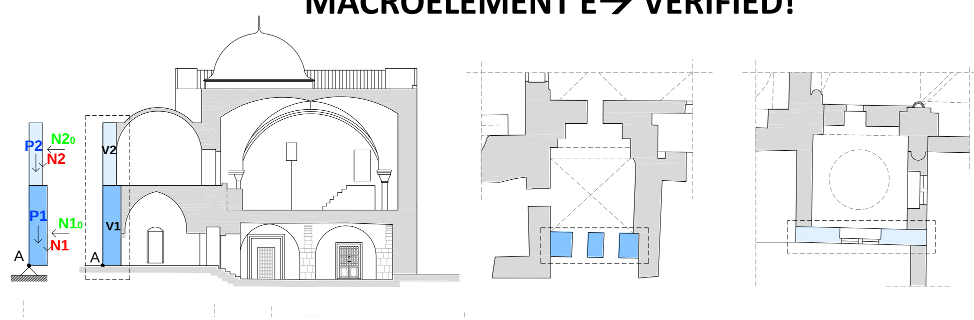


GLOBAL

LINEAR ANALYSIS								
t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: $a_0^* \geq a_0^*$
0,131	635,62	3506,72	0,181	128,52	0,97	1,36	1,35	YES

NON-LINEAR ANALYSIS					
θ [rad]	$d_{k,0}$ [m]	d_0^* [m]	d_u^* [m]	d_u^* [m]	VERIFICATION: $d_u^* \geq d_u^*$ [m]
0,173	0,463	0,479	0,192	0,064	YES

MACROELEMENT E→ VERIFIED!



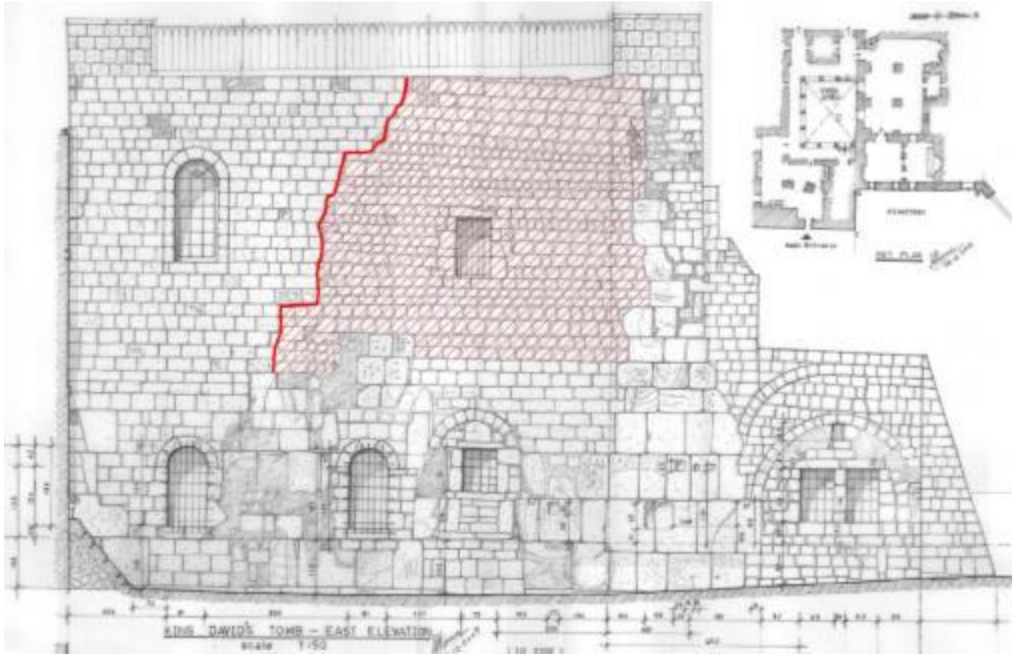
GLOBAL

LINEAR ANALYSIS								
t [m]	M_S [kNm]	M_R [kNm]	α_0	M^* [t]	e^*	a_0^* [m/s²]	a_0^* [m/s²]	VERIFICATION: $a_0^* \geq a_0^*$
0,158	295,87	4958,38	0,060	100,97	0,78	0,558	0,777	NO

NON-LINEAR ANALYSIS					
θ [rad]	$d_{k,0}$ [m]	d_0^* [m]	d_u^* [m]	d_u^* [m]	VERIFICATION: $d_u^* \geq d_u^*$ [m]
0,062	0,241	0,310	0,124	0,079	YES

DESIGN OF INTERVENTIONS

The limit analysis showed that the **most vulnerable structural element** in relation to the seismic risk is the **eastern façade** on the cemetery. The thrusts of the barrel vault on the ground floor and of the vault and cupola on the first floor are particularly high and induce to a precarious stability condition of the whole structural system. This is also testifies by the fact that most likely the façade has been reconstructed several times during centuries, since it is possible to recognize different kind of stone and different textures and arrangements of stones in the façade's elevation



DESIGN OF INTERVENTIONS

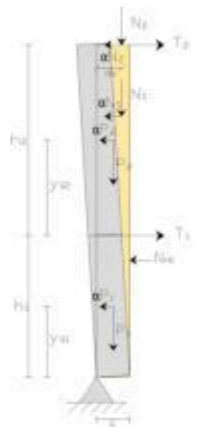
1. GROUT INJECTIONS

MAIN PHASES

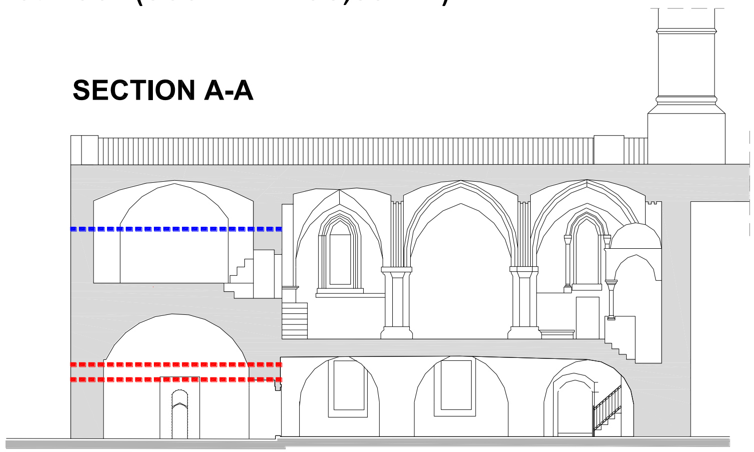
1. Choice of the injection point and of the layout, according to the masonry characteristic (presence of cracks, porosity, geometry, etc.); 2-3 injections point/m^2 could be effective;
2. Removal of the damaged plaster and crack filling (to avoid loss of grouts);
3. Hole drilling (diameter: 40 mm);
4. Positioning of the injection devices and repointing by mortar;
5. Preliminary water injection in order to remove dust and disaggregate materials but also to saturate the wall, avoiding the masonry suction;
6. Evaluation of the injection pressure;
7. Grout injection, starting from the perimeter area of the base.

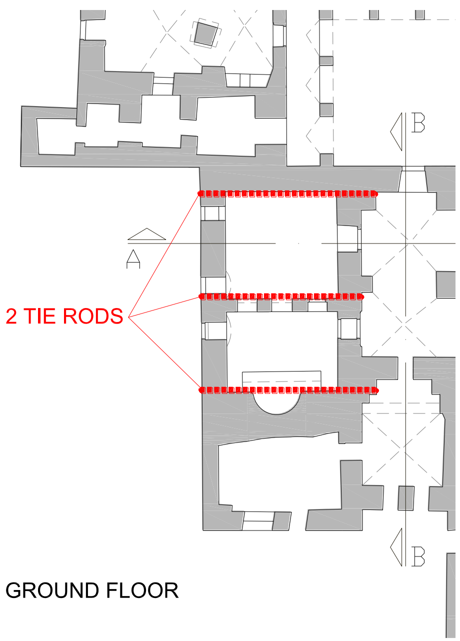
DESIGN OF INTERVENTIONS

2. INSERTION OF TIES

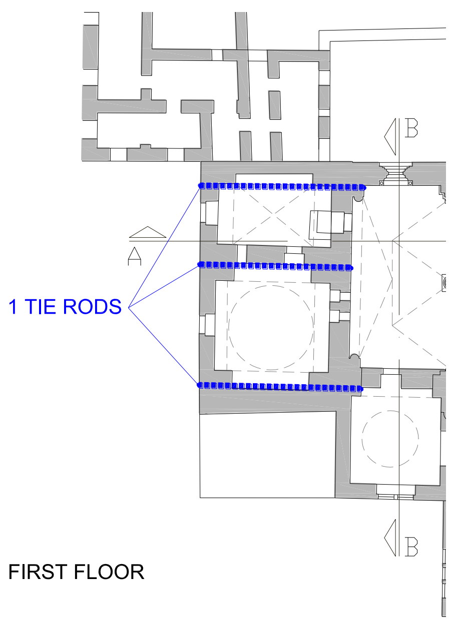


- 6 tie rods on the ground floor (600 kN > 575,86 kN)
- 3 tie rods on the first floor (300 kN > 258,39 kN)

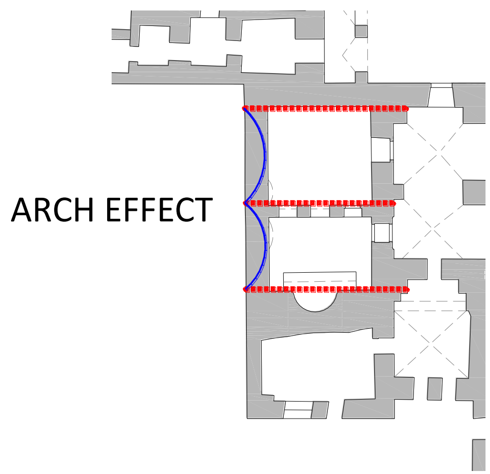




GROUND FLOOR

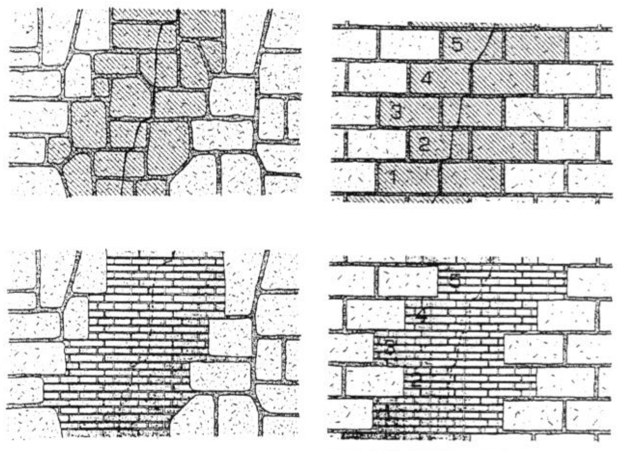


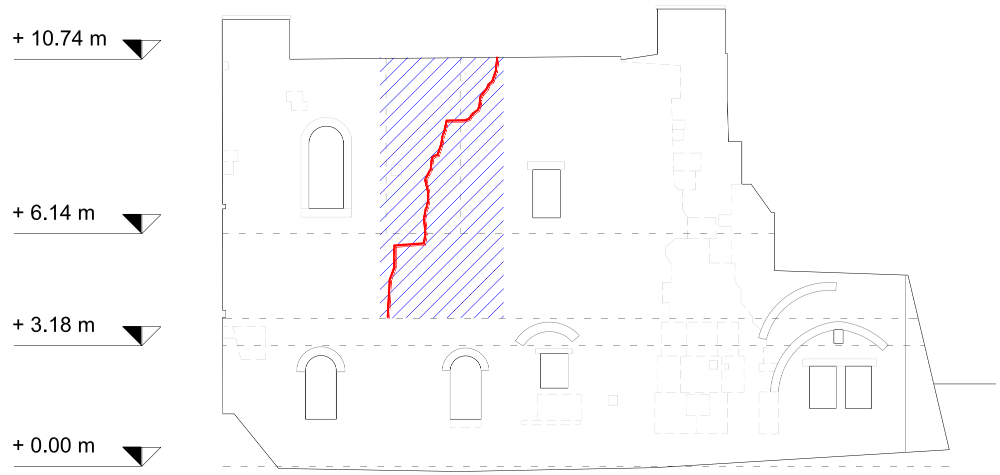
FIRST FLOOR

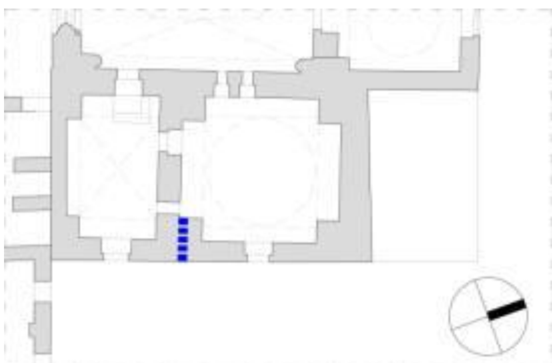


DESIGN OF INTERVENTIONS

3. LOCAL REBUILDING (“SCUCI-CUCI”) AND INSERTION OF TIE RODS IN THE WALL THICKNESS







In addition to the local rebuilding in the area where the “scuci-cuci technique” is applied it is suggested to connect the external leaf of the masonry wall with the internal one in order to avoid the mechanism of layers’ delamination (overturning of the external leaf) by inserting steel tie rods in the masonry thickness

THANK YOU FOR YOUR KIND ATTENTION!

Speaker: Dr. Eng. Filippo Lorenzoni

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