THE CASE OF THE MAIN CHURCH OF DAFNI MONASTERY

E.Vintzileou, National Technical University of Athens, Greece

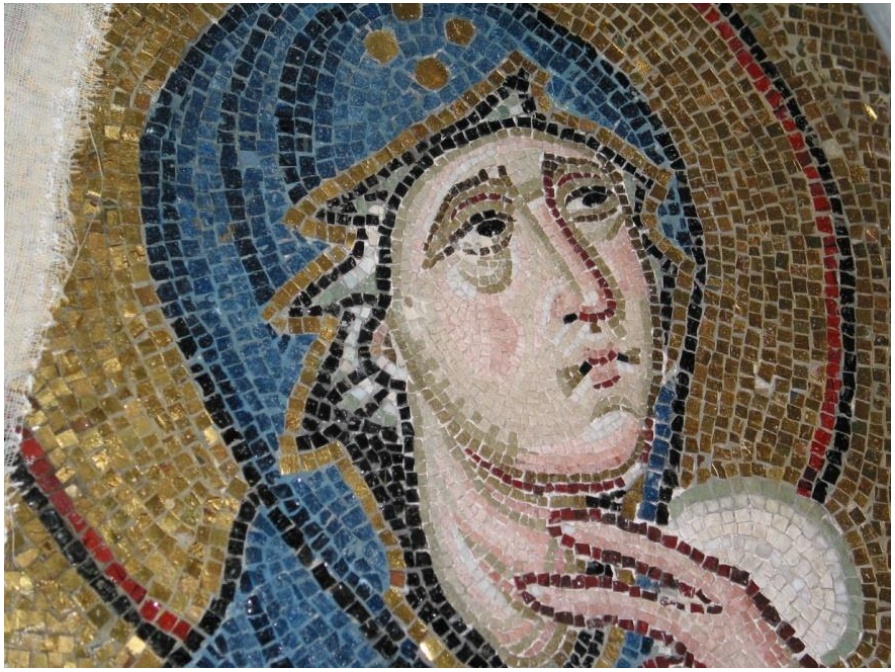
Team: A.Miltiadou-Fezans, N.Delinikolas, Ch.Mouzakis, J.Dourakopoulos, P.Giannopoulos

10km from Athens, on the Holy Road (Iera Odos) leading from the Athens Acropolis to Eleusis. Most probably, founded on an ancient temple of Apollo

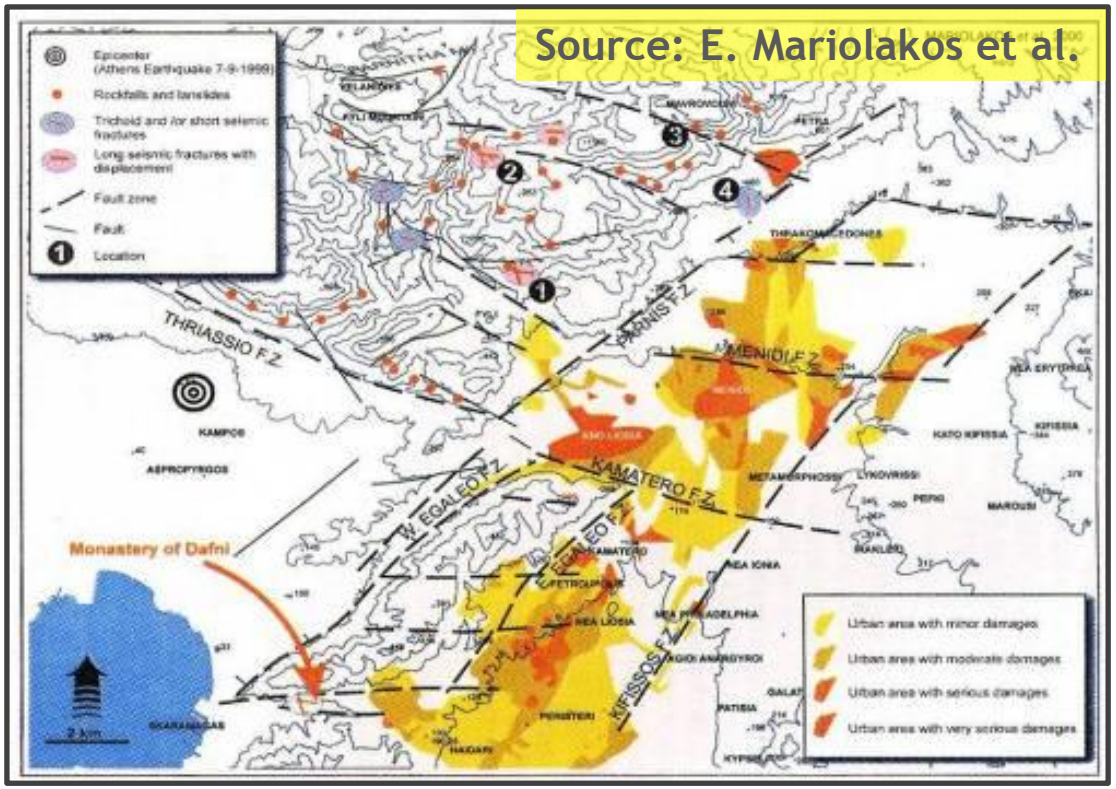
12th-century mosaics

29,10m long, 15,60m wide and 16,20m high (at the centre of the dome.
The church was built in the 11th century.

Pantocrator



Portraits of persons and not typical faces (e.g. of young or old people)



Situated close to active faults.
Severely damaged (several times through the centuries).

Earthquakes known to have affected the monument

YEAR	Ms	LOCATION
1837	6,2	Hydra
1853	6,8	Thebes
1858	6,7	Corinth
1876	6,1	Corinth
1887	6,3	Corinth
1891	6,3	Kythnos
1894	7,0	Atalanti
1928	6,3	Corinth
1938	6,0	Attica
1948	6,4	Spetses
1981	6,7	Corinth
1981	6,4	Boeotia
1981	6,4	Boeotia
1999	5,9	Attica

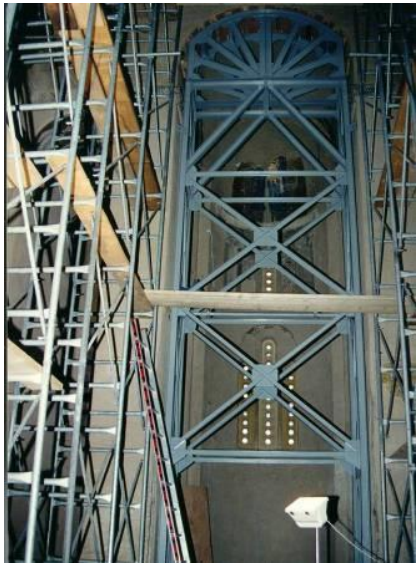
Earthquake September 7th, 1999

Severe damage

- Main church
- Walls
- Buildings

Immediate measure: Collection and identification. Positioning of protective nets to all mosaics

Immediate measures and installation of scaffolding (4-5 levels of work). Measuring the width of cracks to 80 locations



Program of investigations set up by the Ministry of Culture (funded by the Greek State and European Union)

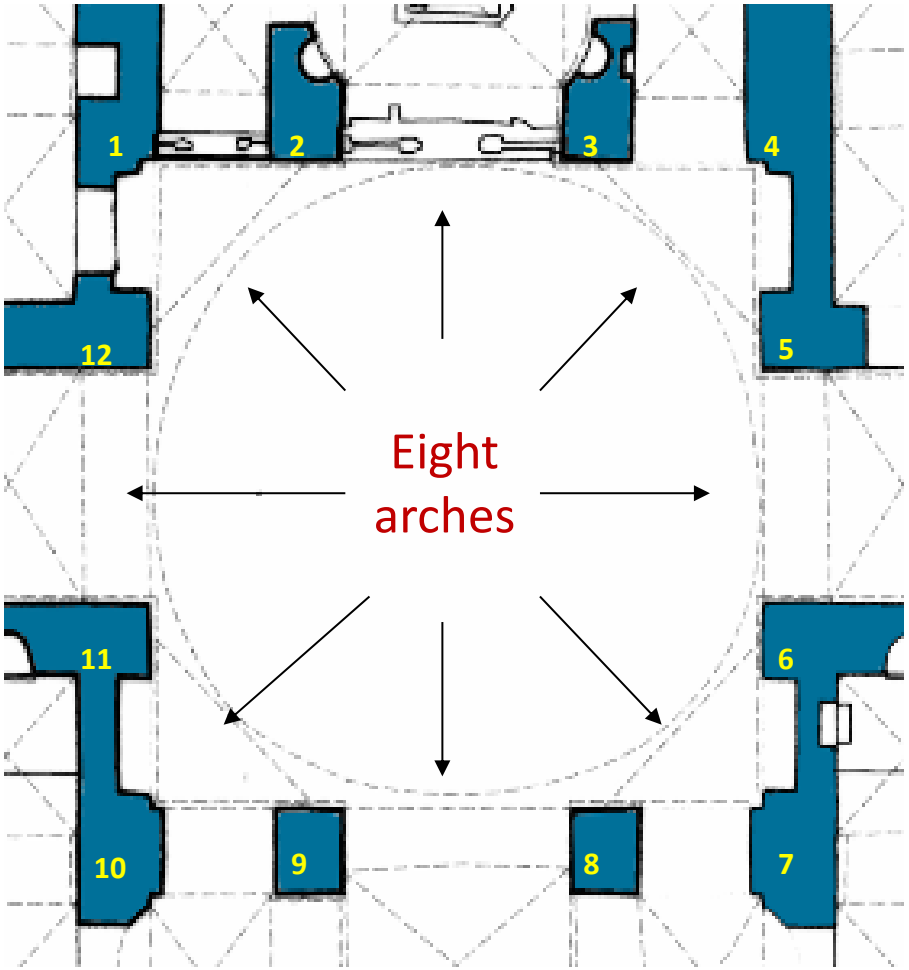
- Survey of pathology
- Study of historical pathology
- Sampling and identification of materials
- Identification of type of construction of masonry (radar/boroscopy)
- Tests on wallettes and shaking table tests on a cross-vault
- Monitoring of response to seismic events and monitoring of cracks

First phase of interventions (grouting of masonry)

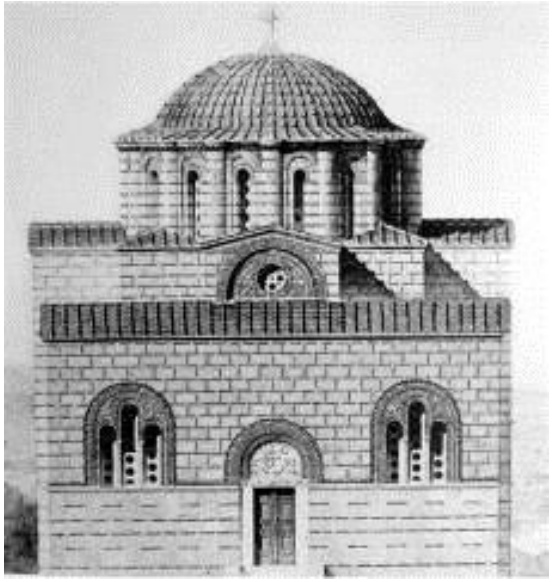
- Investigation of non-visible elements

Study of second phase of interventions, approval by the Central Archaeological Council and Application

The church belongs to the so-called octagonal type: Large free space but high vulnerability

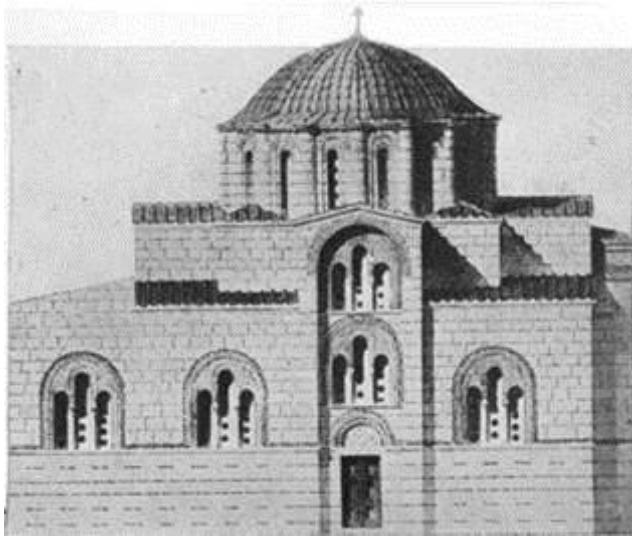


The central dome is supported by 12 piers (in a square arrangement) and by the pendatives



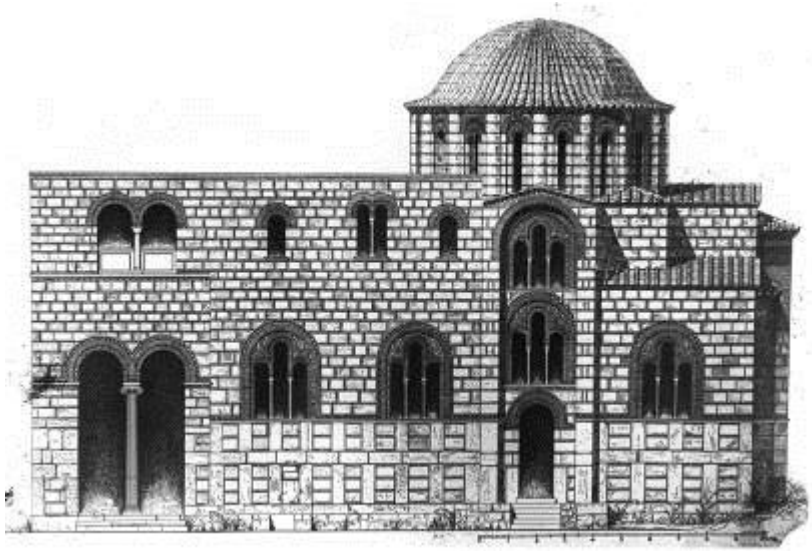
A΄ BYZANTINE PHASE

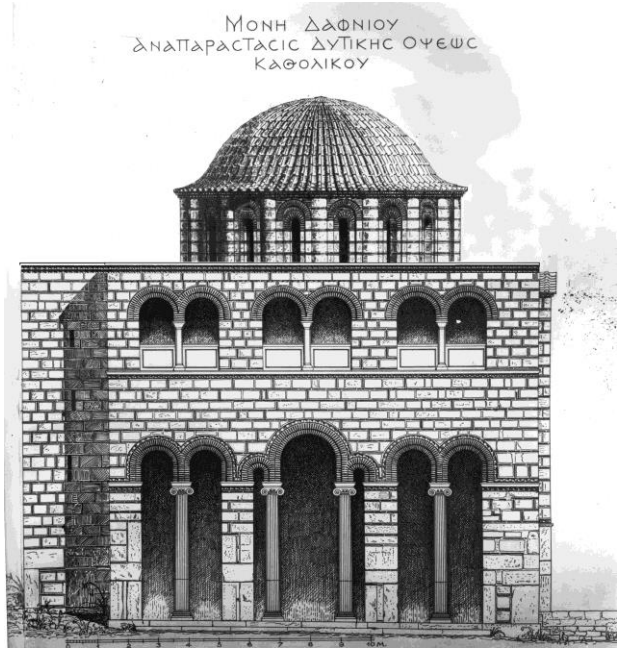
Benouville 1877 and corrected by Delinikolas



B΄ BYZANTINE PHASE

The exo-narthex and a storey were added (Stikas and Delinikolas)



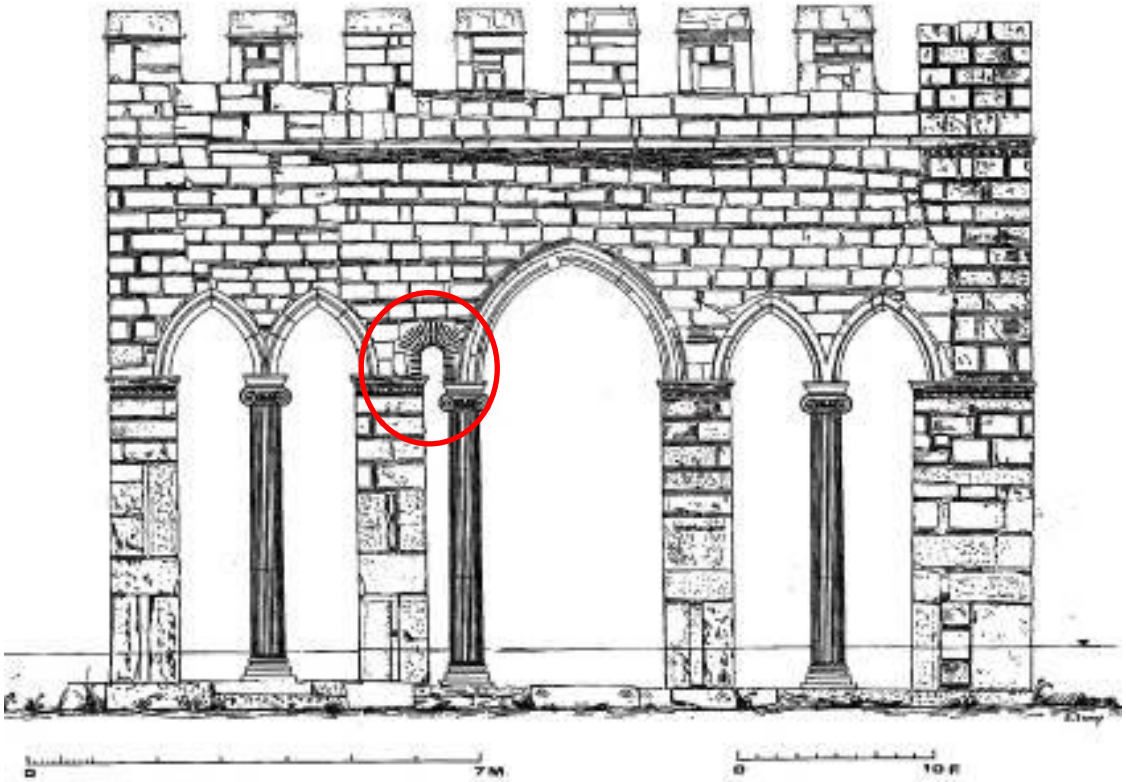


13th century: Strong earthquakes, severe damage, collapse of the roof of the exo-narthex

Cistercian Monks: Extensive interventions to the western part of the church (gothic arches, ramparts, timber roof,…)

THIRD PHASE

During Franks' occupation. Representation by Ch.Bouras



Under the Ottoman Empire: Further severe damage. The church is out of use

Lithograph by Théodore Achille Louis, Vicomte du Moncel, (1843-45)

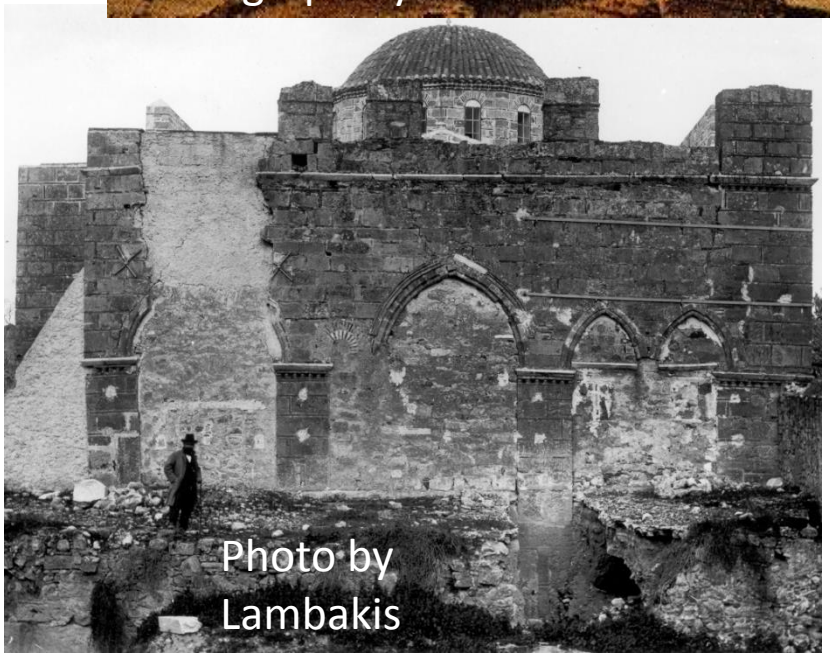
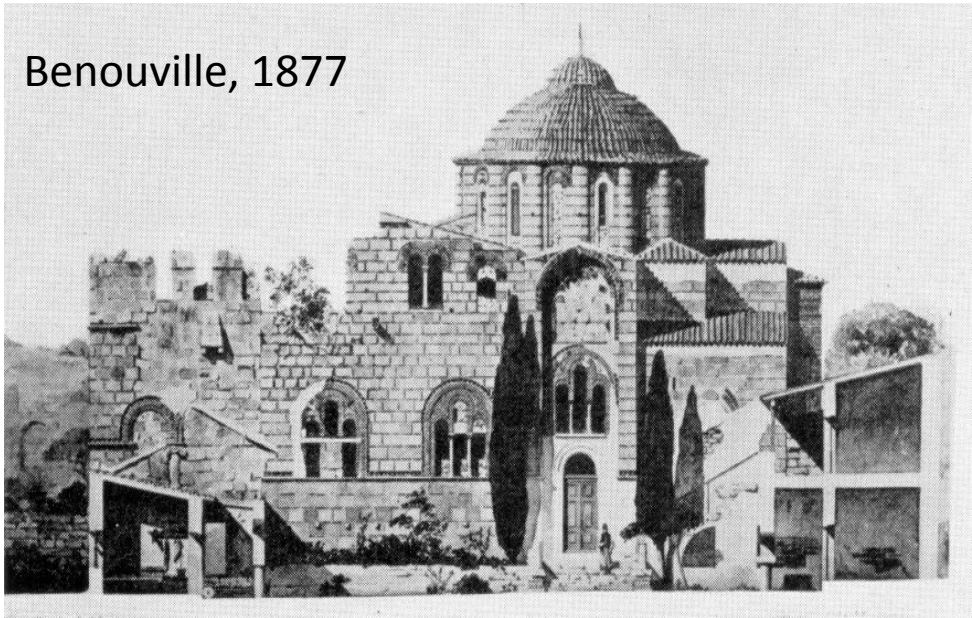


Photo by Lambakis

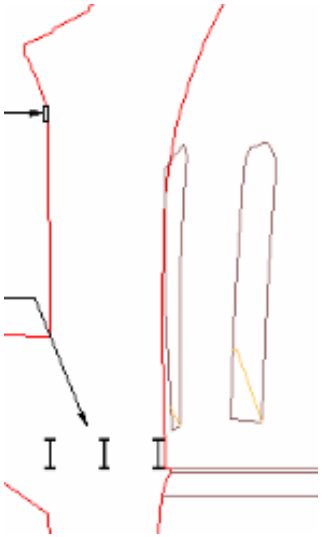


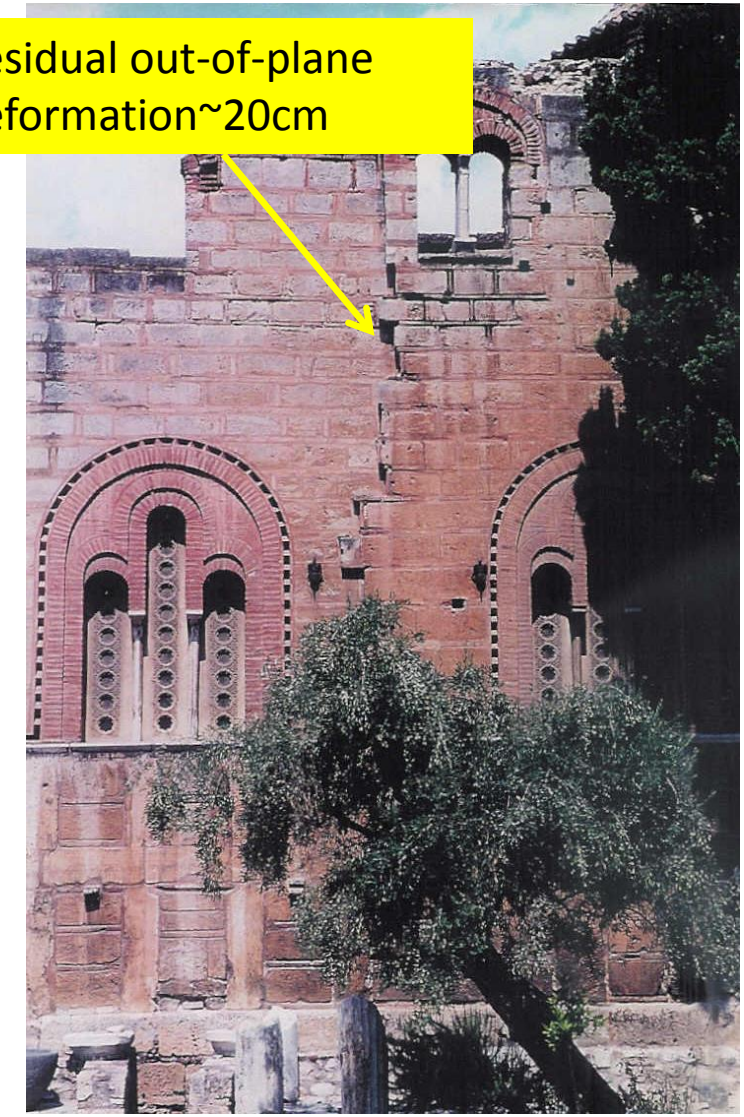
Benouville, 1877

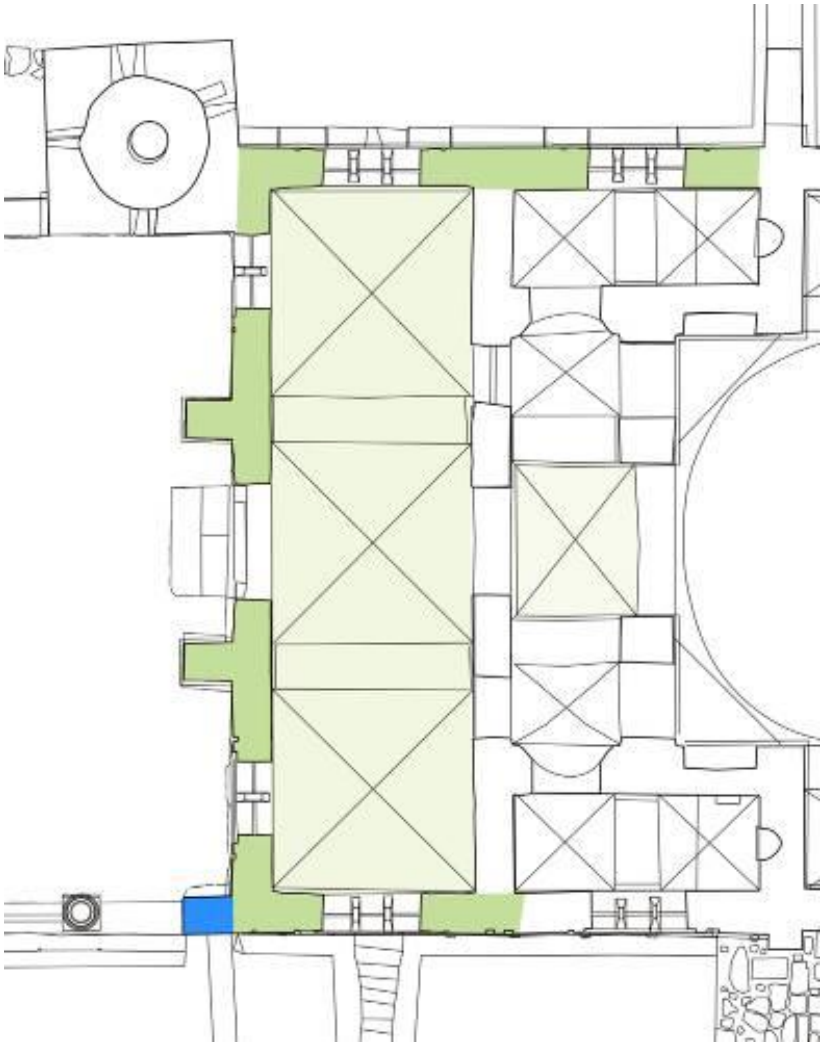
Original dome

Reconstructed dome, 1890-1891

Positioning of three metallic rings at the base of the drum

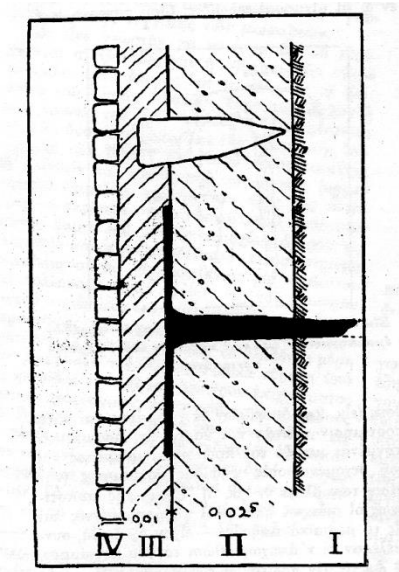






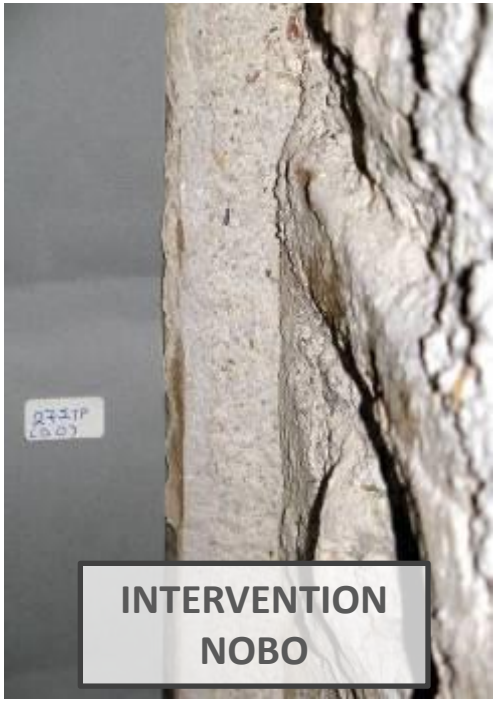
Reconstruction of the narthex, cross vaults of the NW chapel, etc (Troump, 1894-1895)

Obviously, the mosaics were removed and…



Εἰκ. 3. Κονιάματα καὶ σύνδεσμοι τούτων διὰ σιδηρῶν ἥλων καὶ ψηφίδων εἰς σχῆμα σφηνῶν (Ι τοῖχος, ΙΙ α' κονίαμα, ΙΙΙ β' κονίαμα, IV μωσαϊκόν).

BYZANTINE

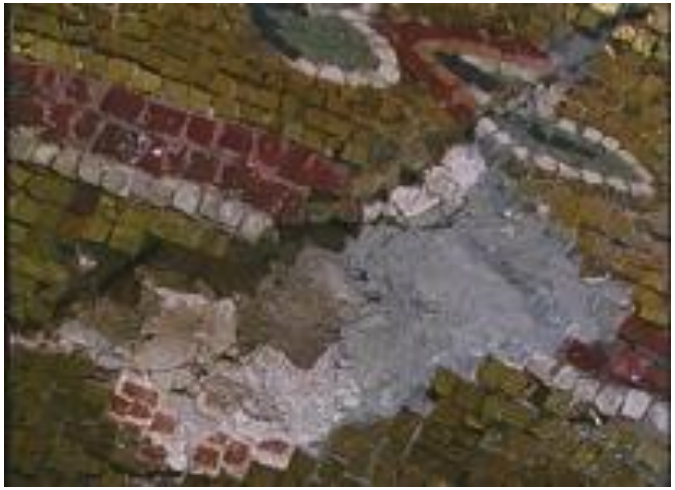


INTERVENTION NOBO

BYZANTINE

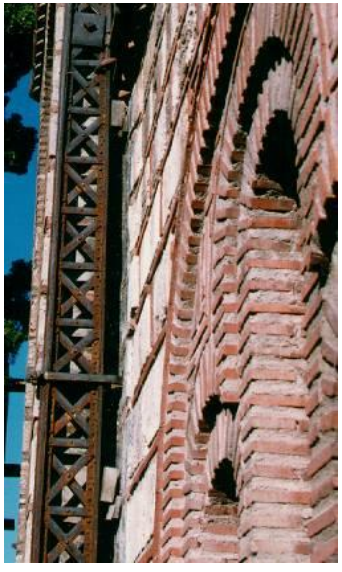
MORE RECENT INTERVENTIONS

…replaced (by Italian conservators, NOBO, 1890-1897), on a substrate made of hydraulic lime



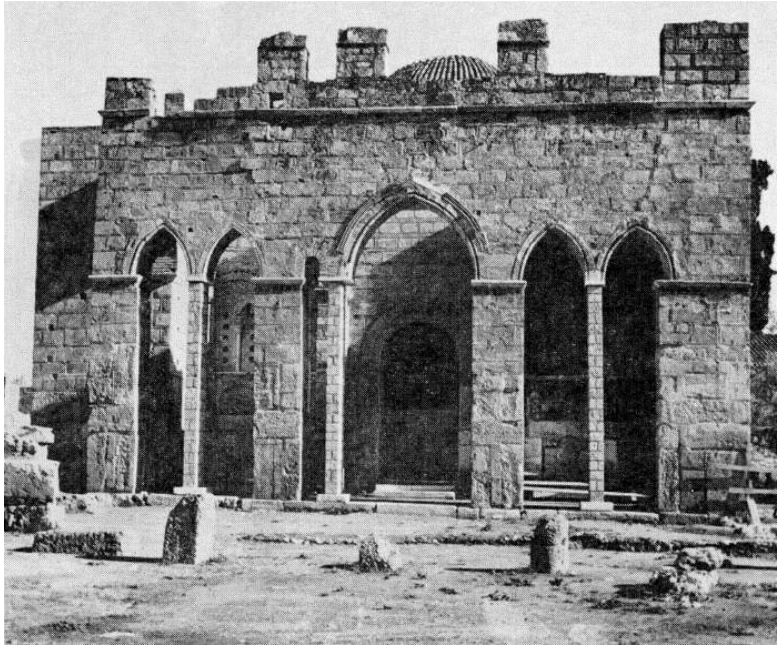
Use of cement

1897-1907:
Two stone masonry buttresses both sides of the N entrance (Troump).

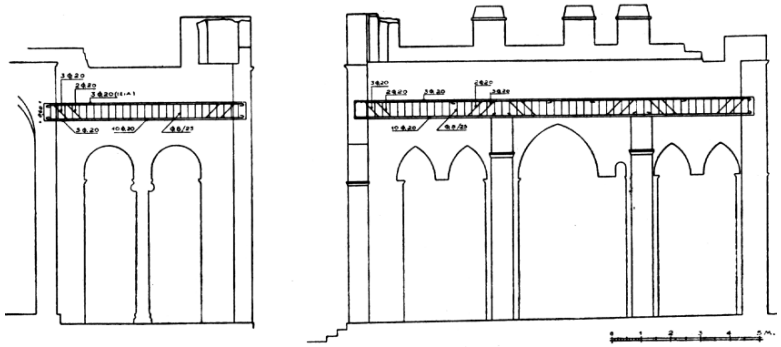


1907:
Metallic confinement of the piers both sides of the S entrance (Adamantiou, Evgeniou).

Piers at the S entrance



1955-1960:
Rehabilitation of the exo-narthex (western part) by Stikas



The columns (removed at an earlier stage-taken by Elgin/British Museum) were replaced by brick masonry "columns"

A reinforced concrete tie beam was constructed along the west façade, as well as along the south face of the exo-narthex.

The construction type of masonry

(a) Two distinct types of masonry (lower and upper regions)

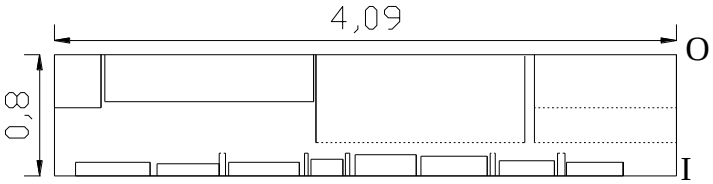
(b) The thickness of masonry (at both regions) ~0,80m

(c) Interior face constructed following a different pattern than the exterior one.

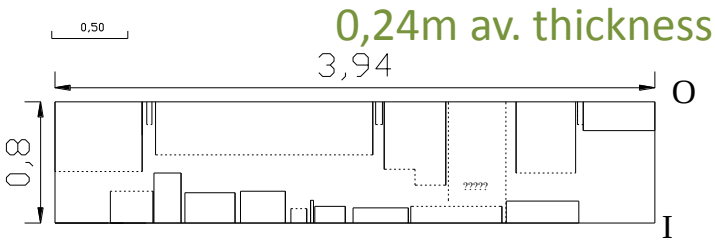
Therefore, a three-leaf type masonry was assumed.

Questions to be answered:

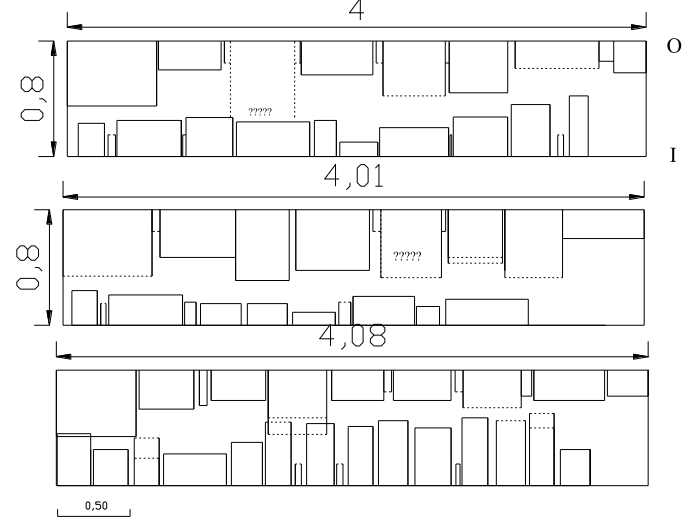
- How is masonry constructed within its thickness, in the two zones?
- Are there header stones connecting the outer leaves?
- Nature of the filling material?



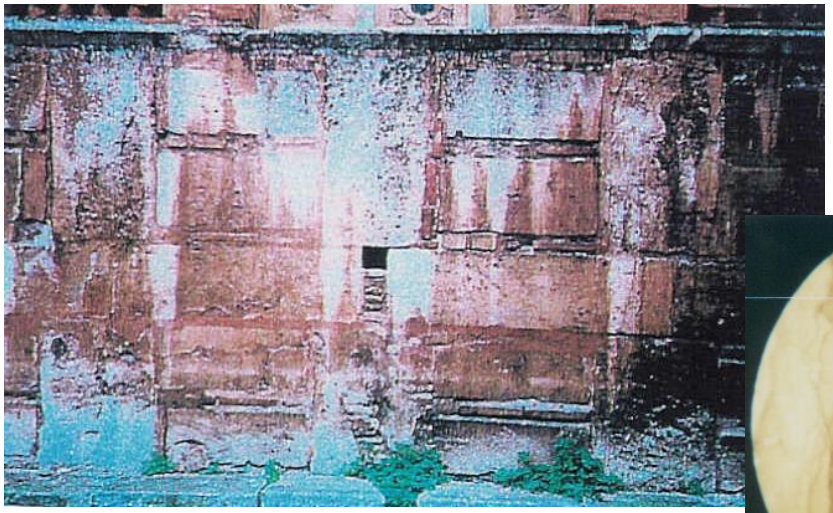
Radar and boroscopy



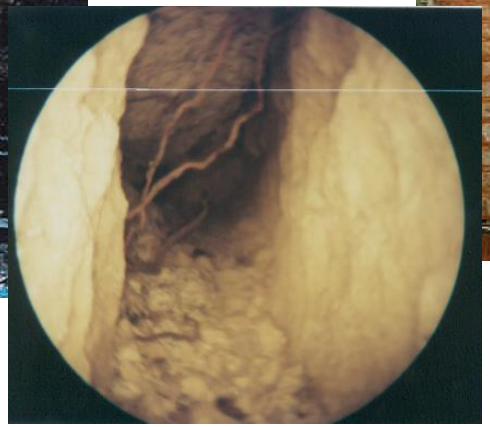
0,24m av. thickness of filling material 0,32m

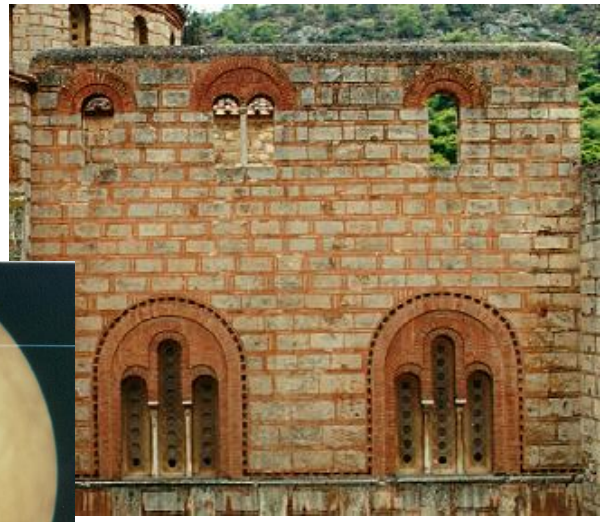


How to estimate the mechanical properties of this (rather peculiar) type of masonry?



The state of filling material





Compr.strength f_c (MPa)
Stones
4,05
13,1
21,16
22.48
Bricks
4,69
5,02
17,7
Mortars
0,21
0,385
0,046

Estimation of mechanical properties of masonry on the basis of the Literature: Very scattered values; the adoption of the most conservative one was not an option

The underestimation of mechanical properties might lead to more extensive interventions than needed

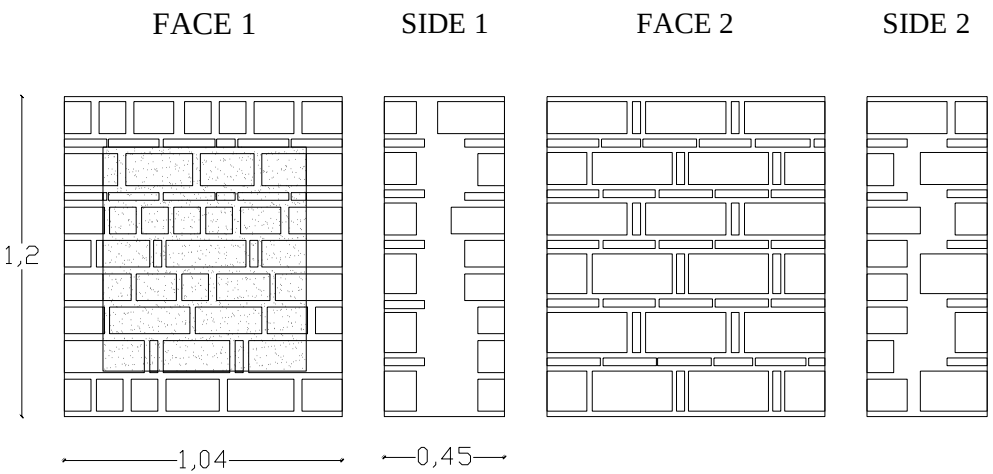
The decision was made to initiate the strengthening of masonry by grouting (+re-pointing)

Assessment of mechanical properties and selection of adequate grout (in laboratory tests)

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

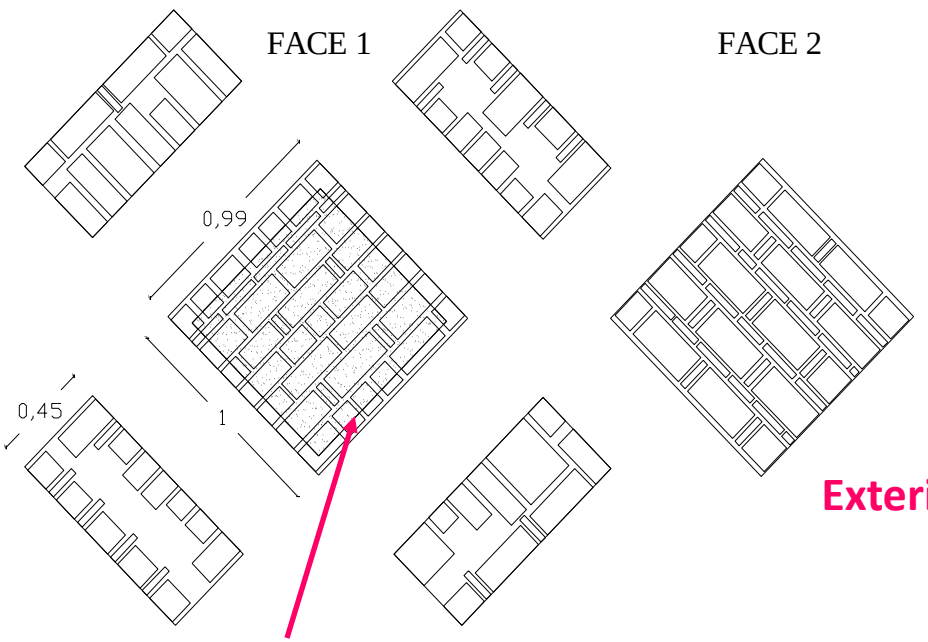
The decision was taken to simulate the masonry of the upper zone (where damages are concentrated).

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY



Wallettes subjected to compression

Interior leaf (+mosaic) **Exterior leaf**



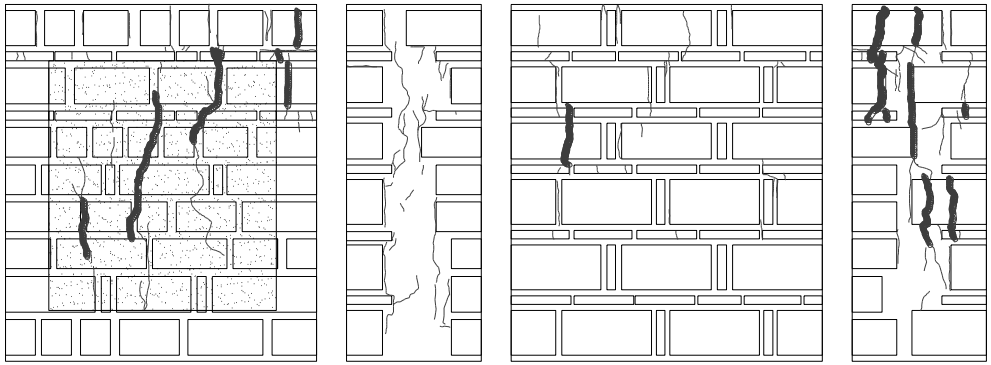
Wallettes subjected to diagonal compression

Exterior leaf

Interior leaf (+mosaic)

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

Wallettes in compression

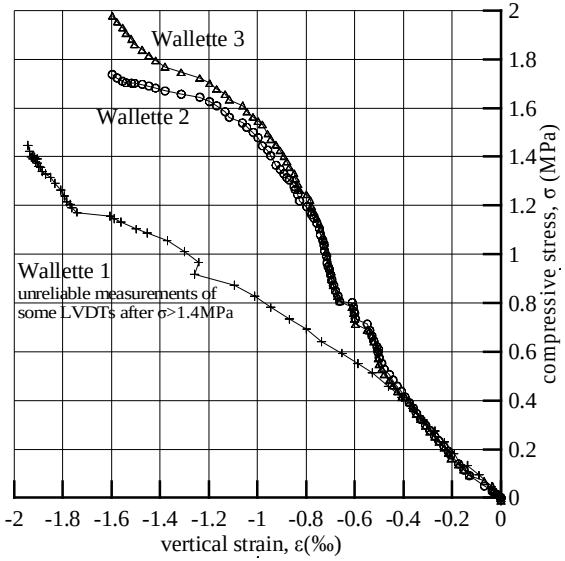


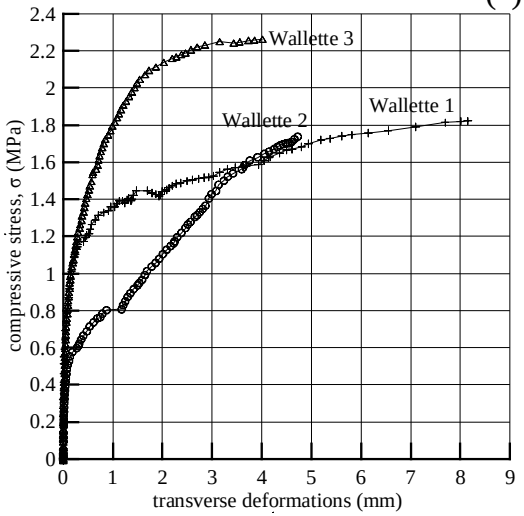
FACE 1 SIDE 1 FACE 2 SIDE 2

Failure mechanism:
Opening of vertical cracks and opening of transverse cracks

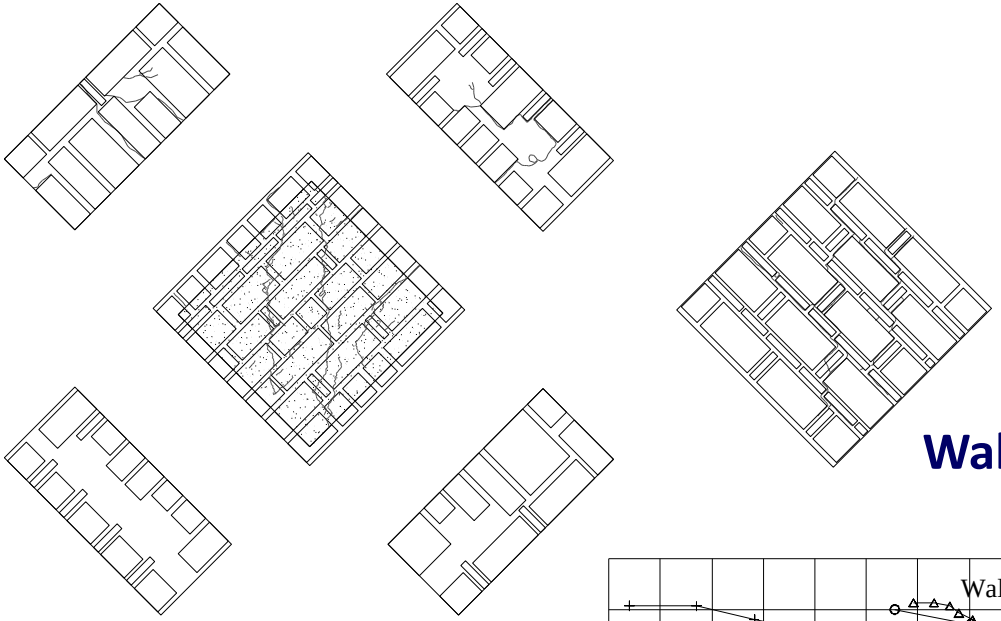
Wallette	σ_{max} *(MPa)*	ε_v ($^0/_{00}$)	E_0 *(GPa)*	E_0/σ_{max}
1	*1.82*	*	*1.0*	*594.45*
2	*1.74*	*-1.6*	*1.44*	*827.59*
3	*2.26*	*-2.25*	*1.5*	*663.72*

(*) Unreliable measurements of some of the LVDTs

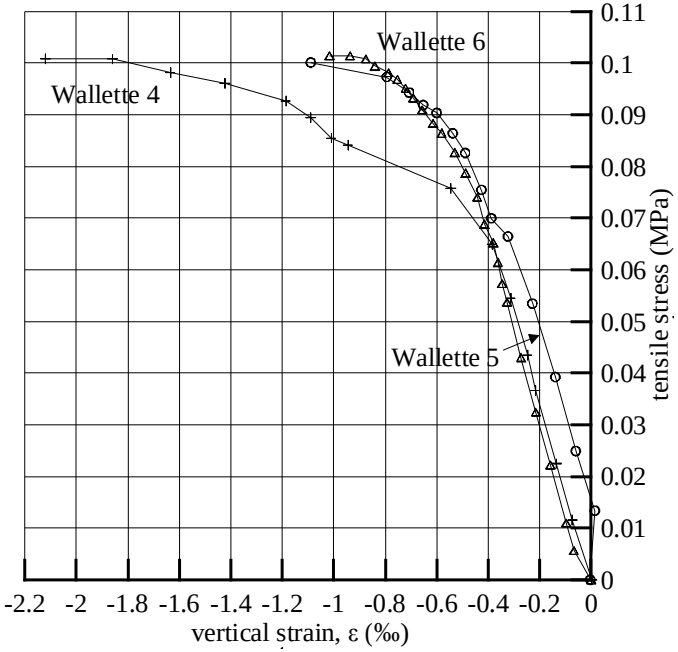




IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY



Wallettes in diagonal compression



Shear strength under zero normal stress~0,1 MPa

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

TERNARY GROUT										
White Danish cement	*Lime (powder)*	*Pozzolan (d_{max}<75μm)*	*Superplas -ticizer SP1*	*Water*	*Compressive (f_{gc}) and flexural (f_{gt}) strength (MPa)*					
					Age (days)					
					28		*90*		*180*	
30	*25*	*45*	*1*	*80*	f_{gc}	f_{gt}	f_{gc}	f_{gt}	f_{gc}	f_{gt}
					4.08	*2.11*	*8.16*	*2.29*	*10.6*	*3.13*
NHL5-BASED GROUT										
NHL5 (St Astier)		*Superplasticizer SP2*		*Water*						
100		*1*		*80*	*2.82*	*2.47*	*4.50*	*2.52*	*6.36*	*3.87*

	T_{36} (sec) Sand column 1.25/2.50 mm (voids ~0.2-0.4 mm)	$t_{d=4.7mm}$ (sec)	Bleeding
TERNARY GROUT	19	20.5	2%
NHL5-BASED GROUT	22.5	22	3%

Two alternative grout mixes were designed. All tests (that are necessary for the assessment of rheological, physical, chemical and mechanical properties of the grout) were carried out.

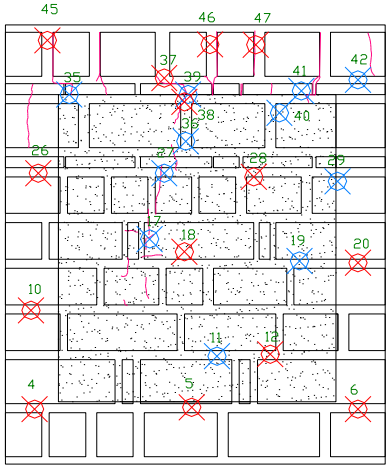
IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

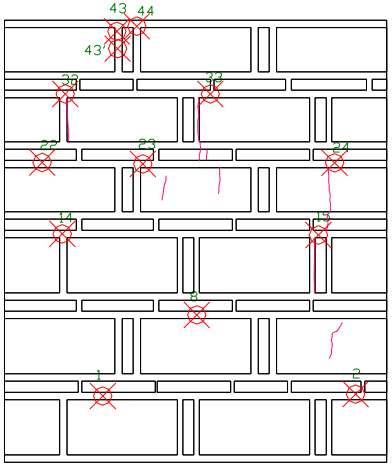
Drilling of holes and installation of plastic tubes

Drilling holes

Sealing cracks

Installing tubes





Tubes are numbered and reported on drawings

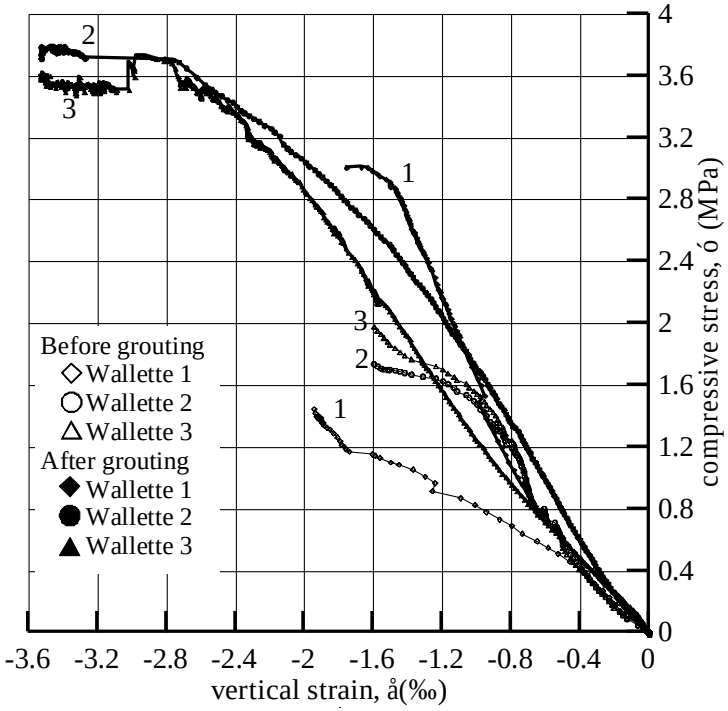
Holes at distances 0.5-1.0m ≤thickness of masonry + along cracks

Holes deep enough to reach filling material

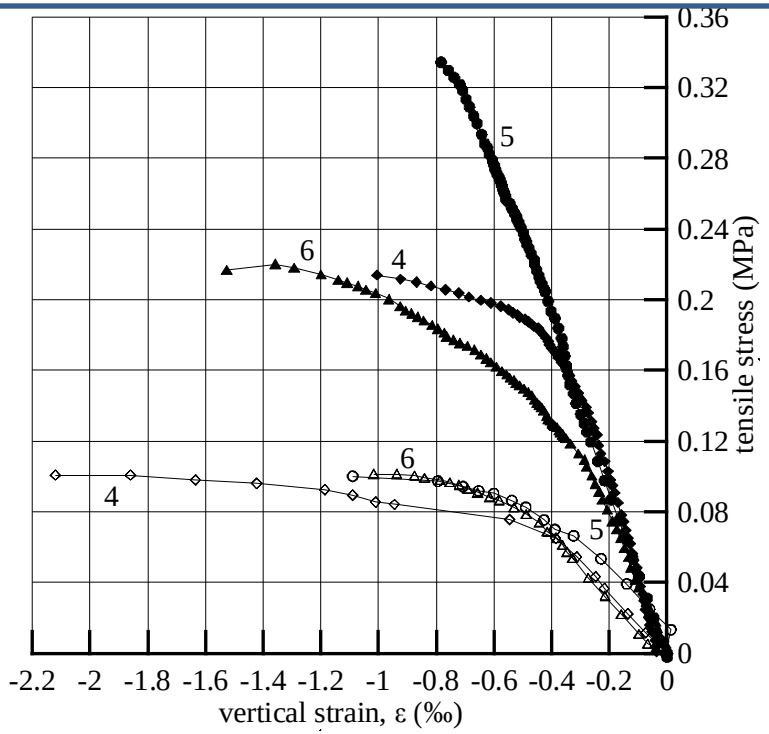
Transparent tubes (1.0 to 10.0mm)

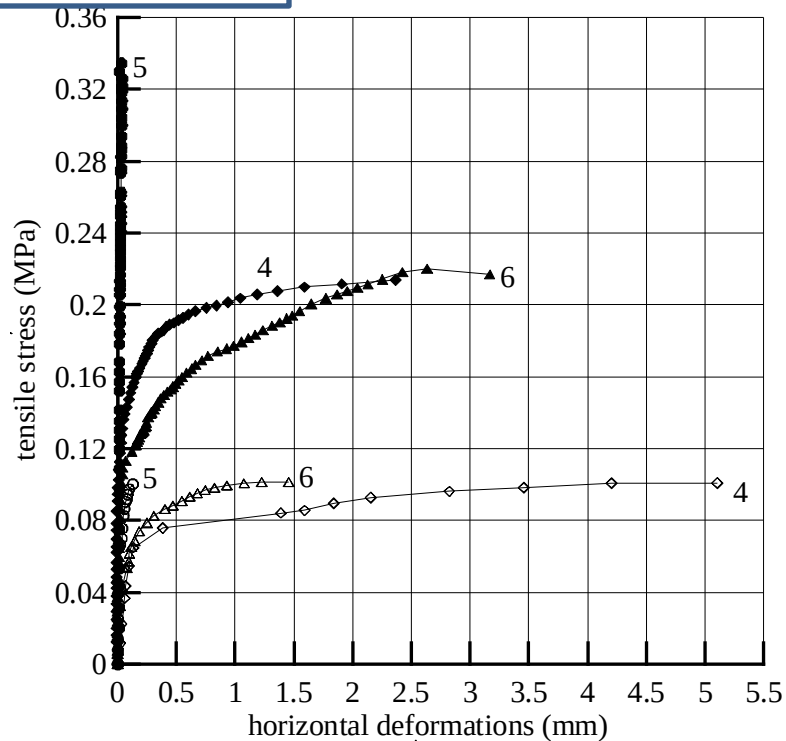
IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

Wallette	f_{w0} (MPa)	f_{ws} (MPa)	f_{ws}/f_{w0}	ε_{v0} (‰)	ε_{vs} (‰)	E_0 (MPa)	E_s (MPa)	E_s/E_0
1	1.82	3.00	1.65	*	-1.76	1,000	1,200	1.20
2	1.74	3.75	2.16	-1.6	-2.50	1,440	1,550	1.08
3	2.26	3.73	1.65	-2.25	-3.39	1,500	1,300	0.87



IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY





BEHAVIOUR OF A CROSS VAULT

TEST 1. as built: Motion along X and Y directions

TEST 2. Strengthened with grouts+steel ties in the arches: Motion along the (strong) X direction.

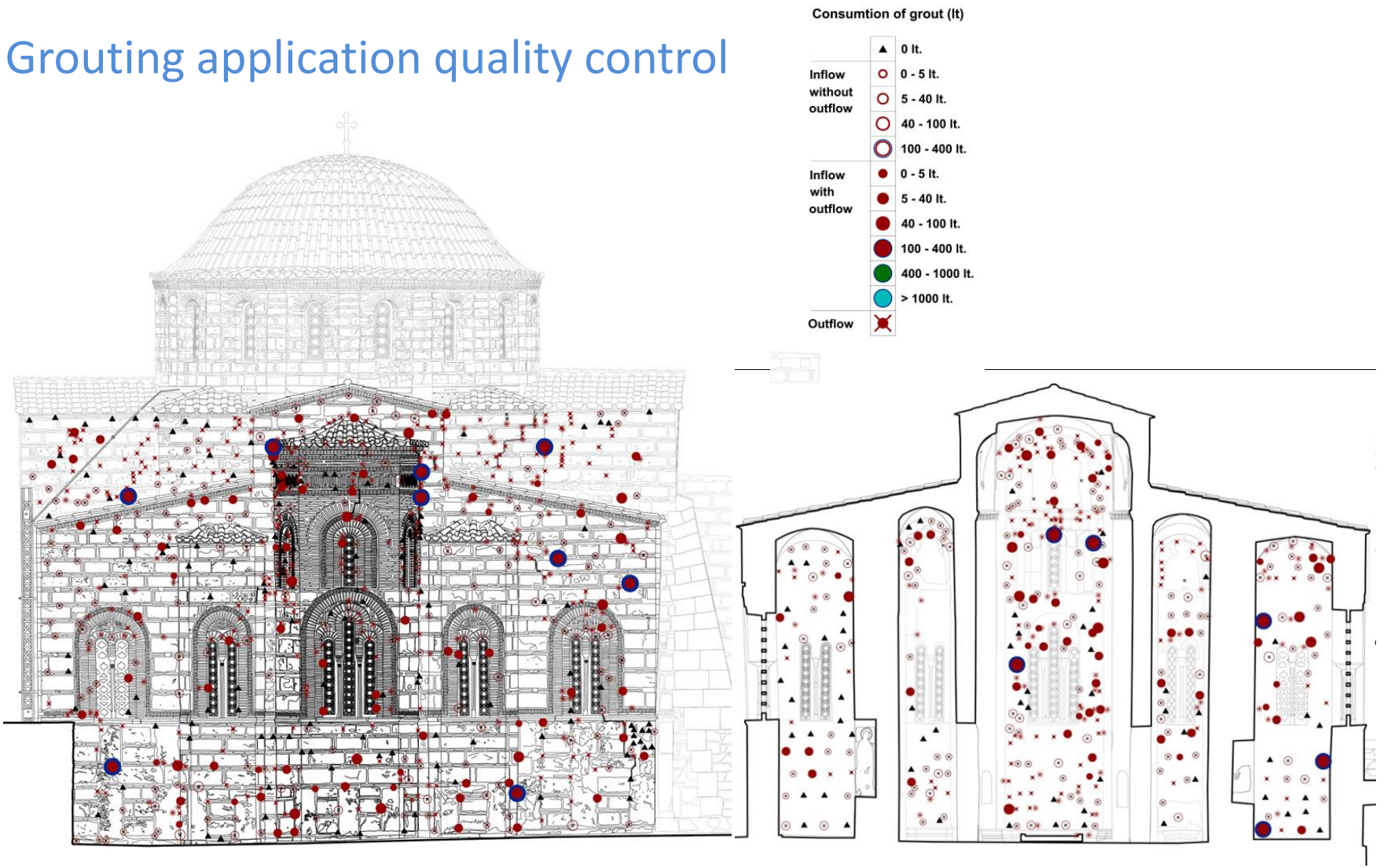
TEST 3. strengthened: Motion along X and Y directions.

1st phase interventions: improving the behaviour of masonry

Grouting masonry elements and mosaics substrata

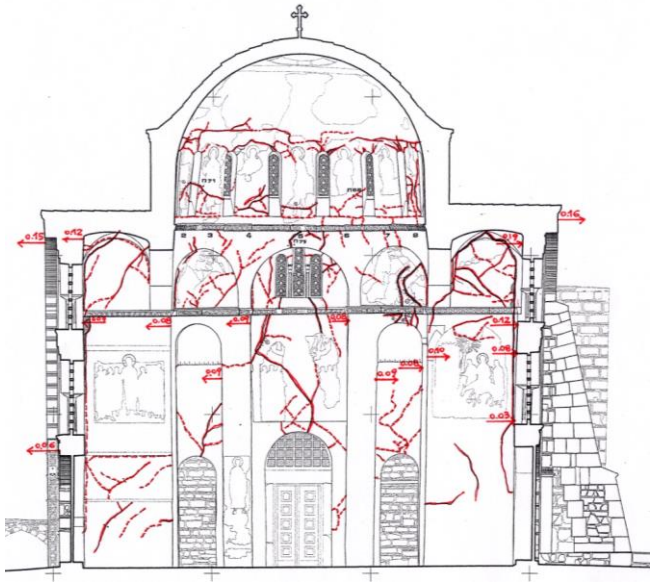
1st phase interventions: improving the behaviour of masonry

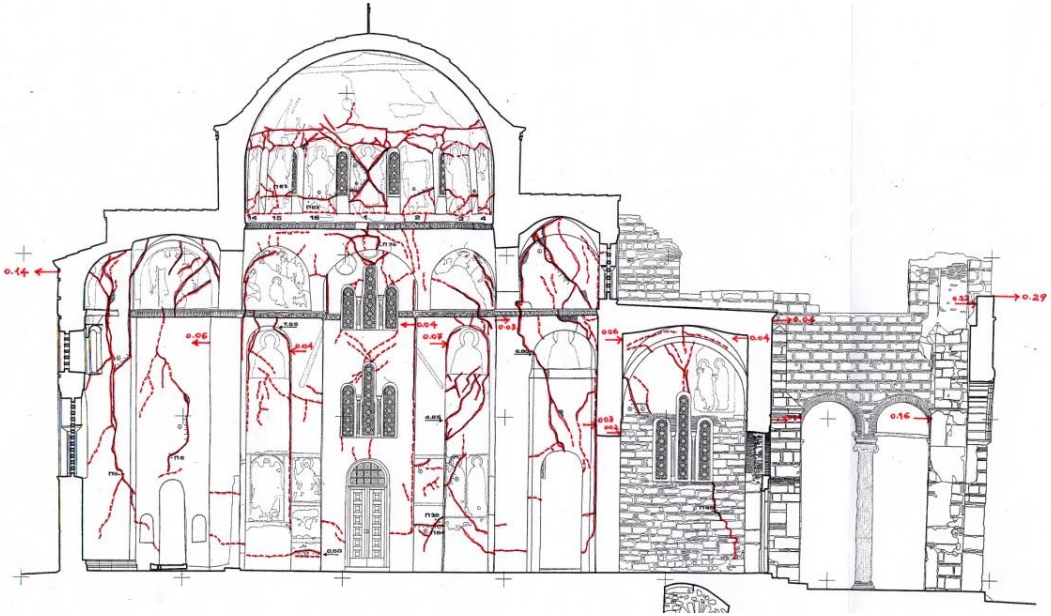
Grouting application quality control

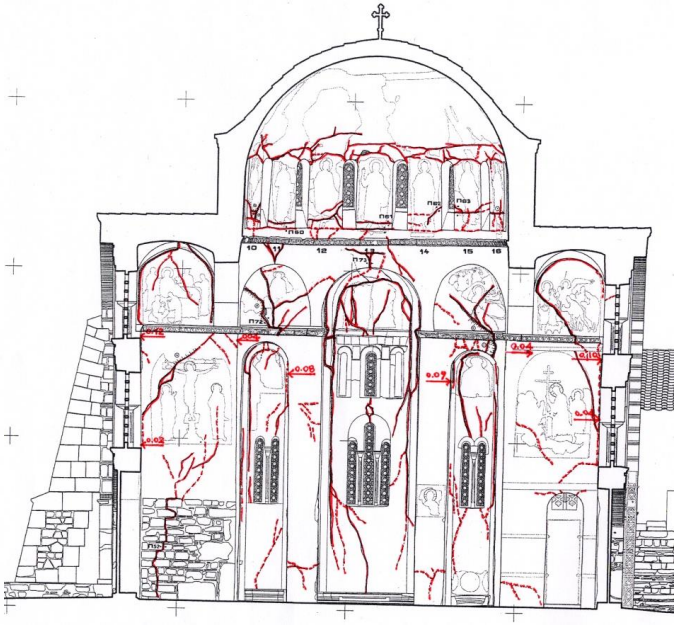


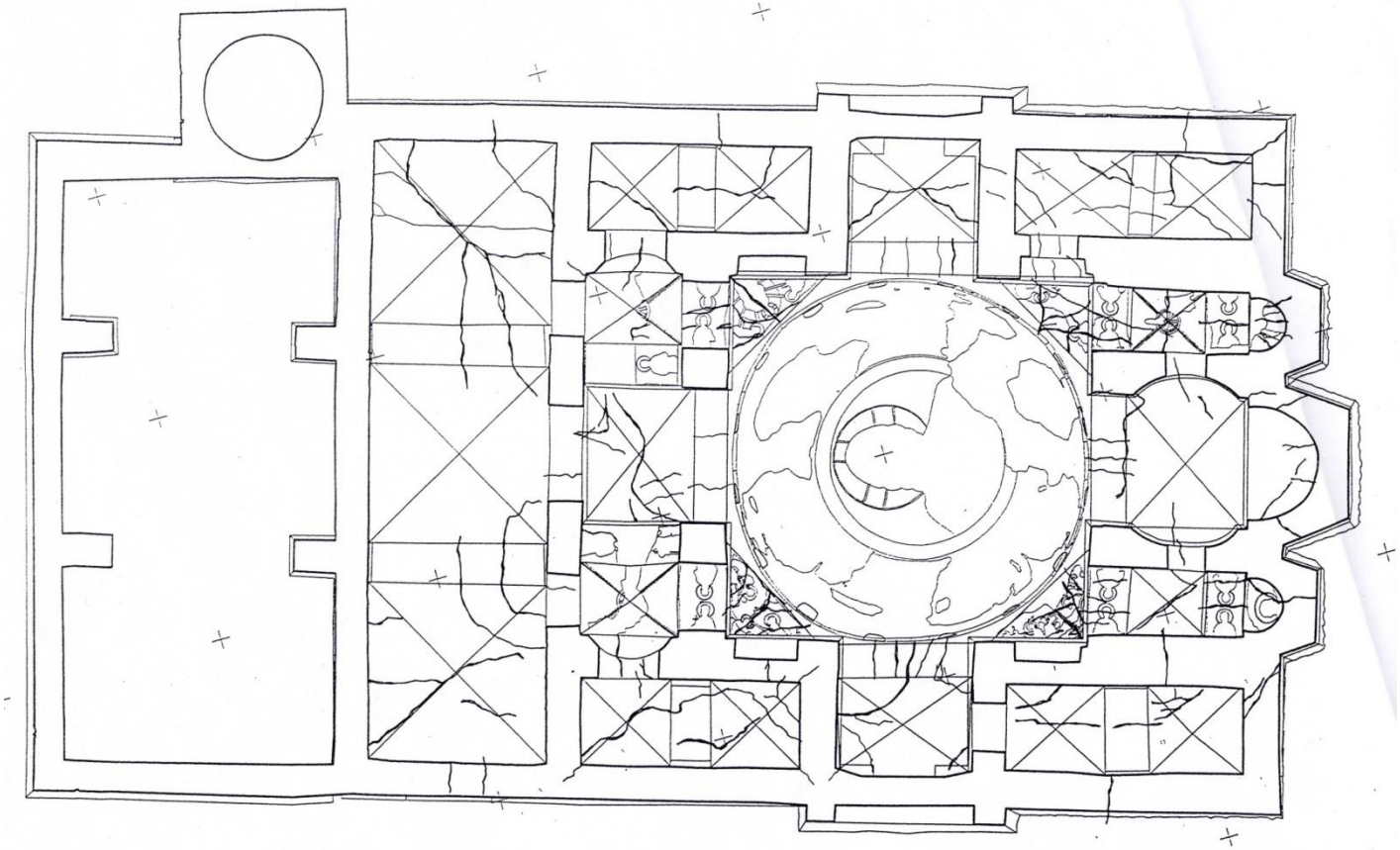
East wall: grout consumption ~ 6.5% of the total volume of the wall

DETAILED SURVEY OF DAMAGE





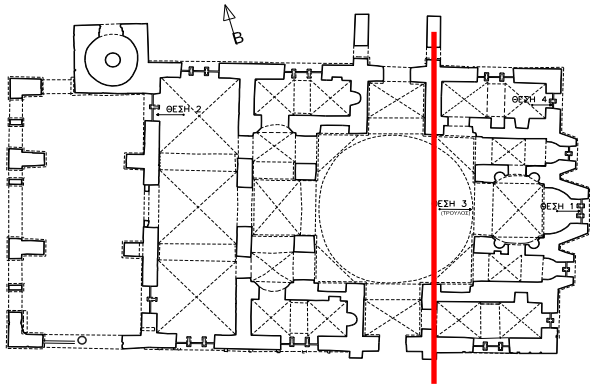




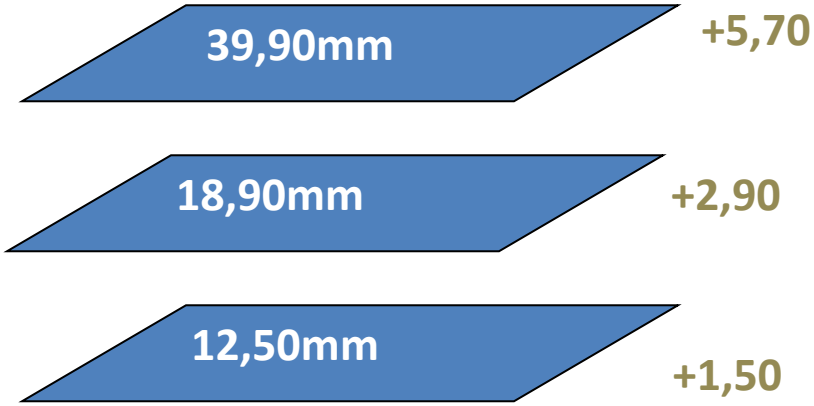
Severe cracking to all arches, cross vaults, pendatives. Many cracks through the mosaics

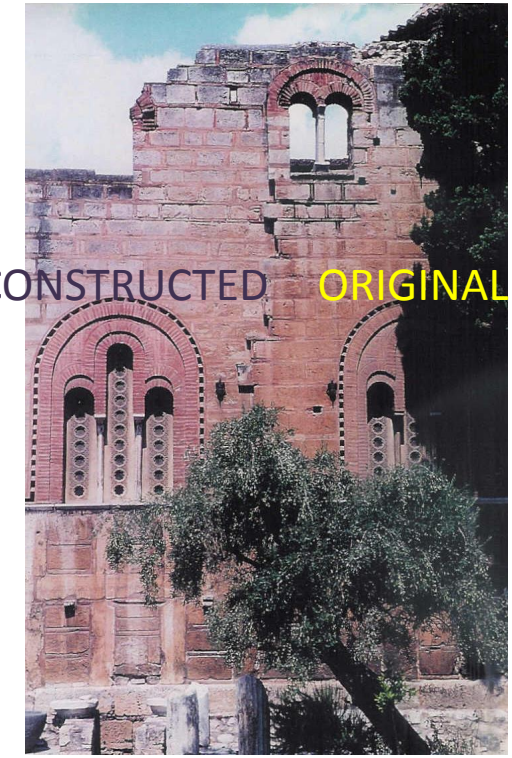
More and more severe damage, at the W-part of the monument and at the upper part of the church (where the mosaics are located).

Pronounced out-of-plane displacement of walls (especially, along N-S direction)

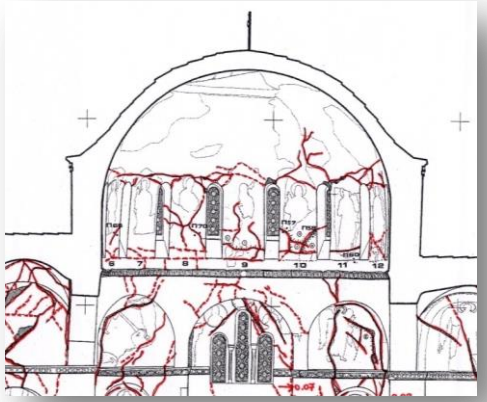


Sum of crack openings in east-west direction

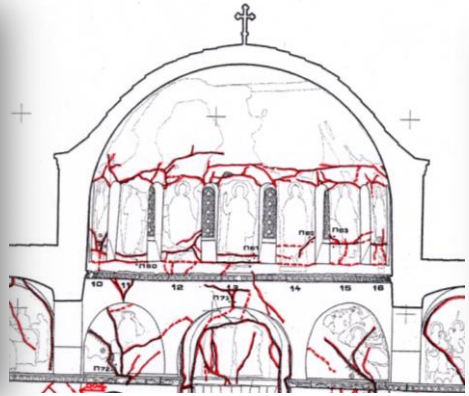




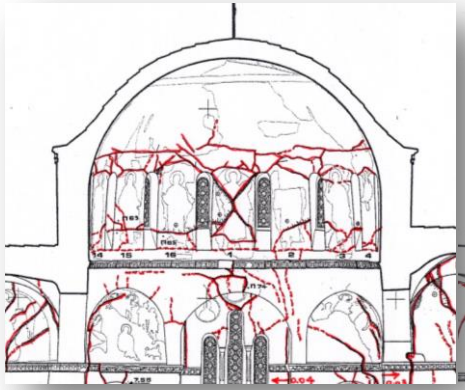
Therefore, there is a tendency of the building "to open" in the north-south direction



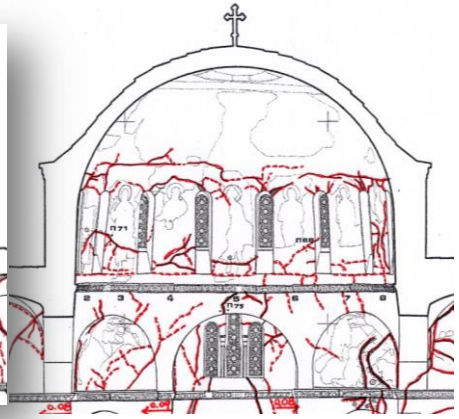
N



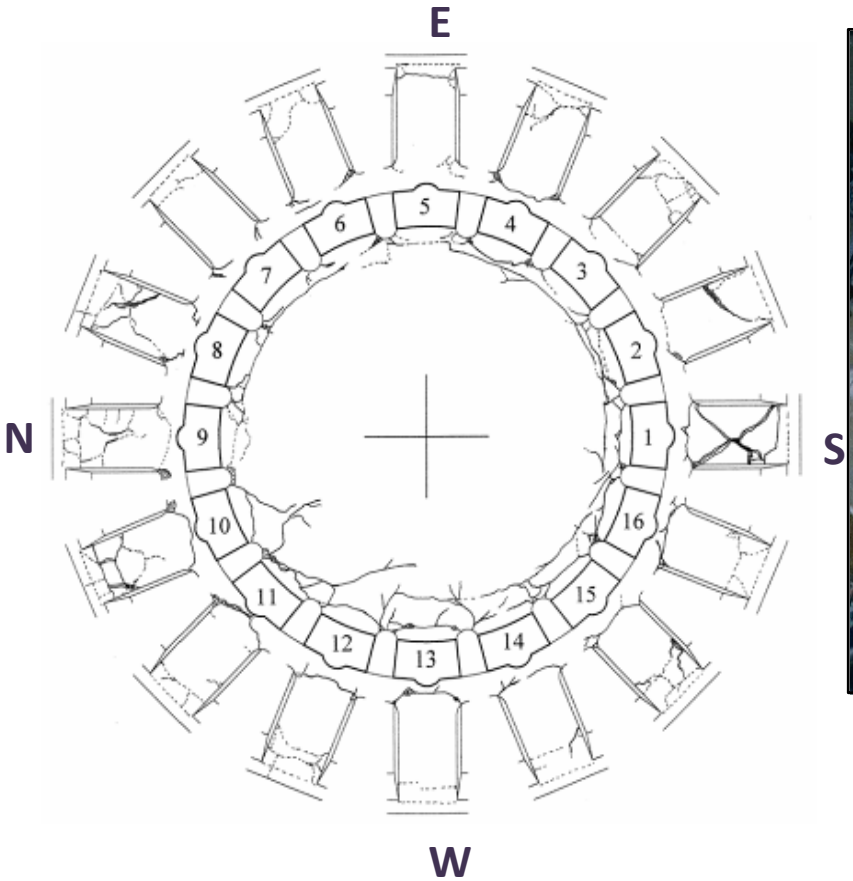
E



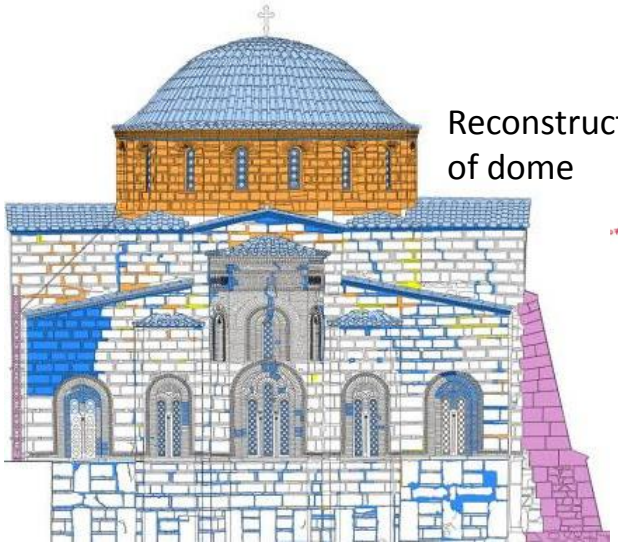
S



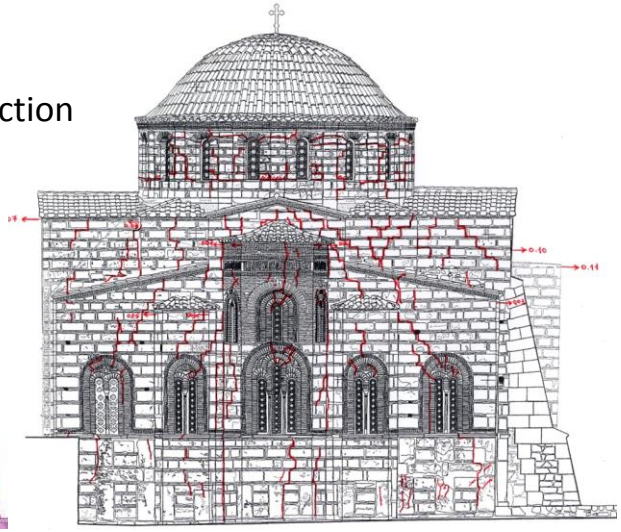
W



Looking South



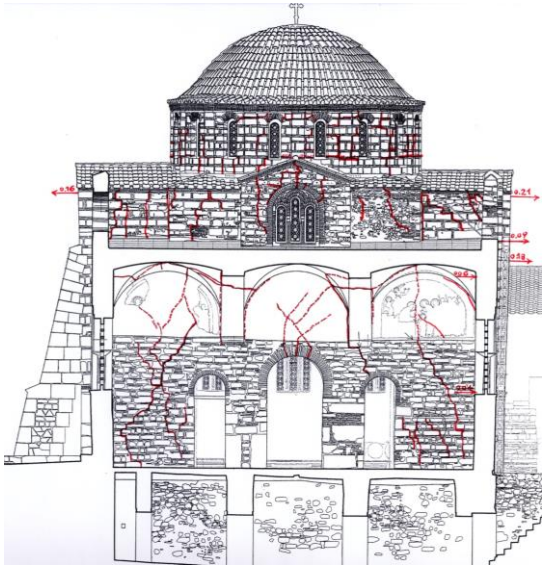
Reconstruction of dome



Confinement of piers

Construction of buttresses

Partial reconstruction of south and west wall



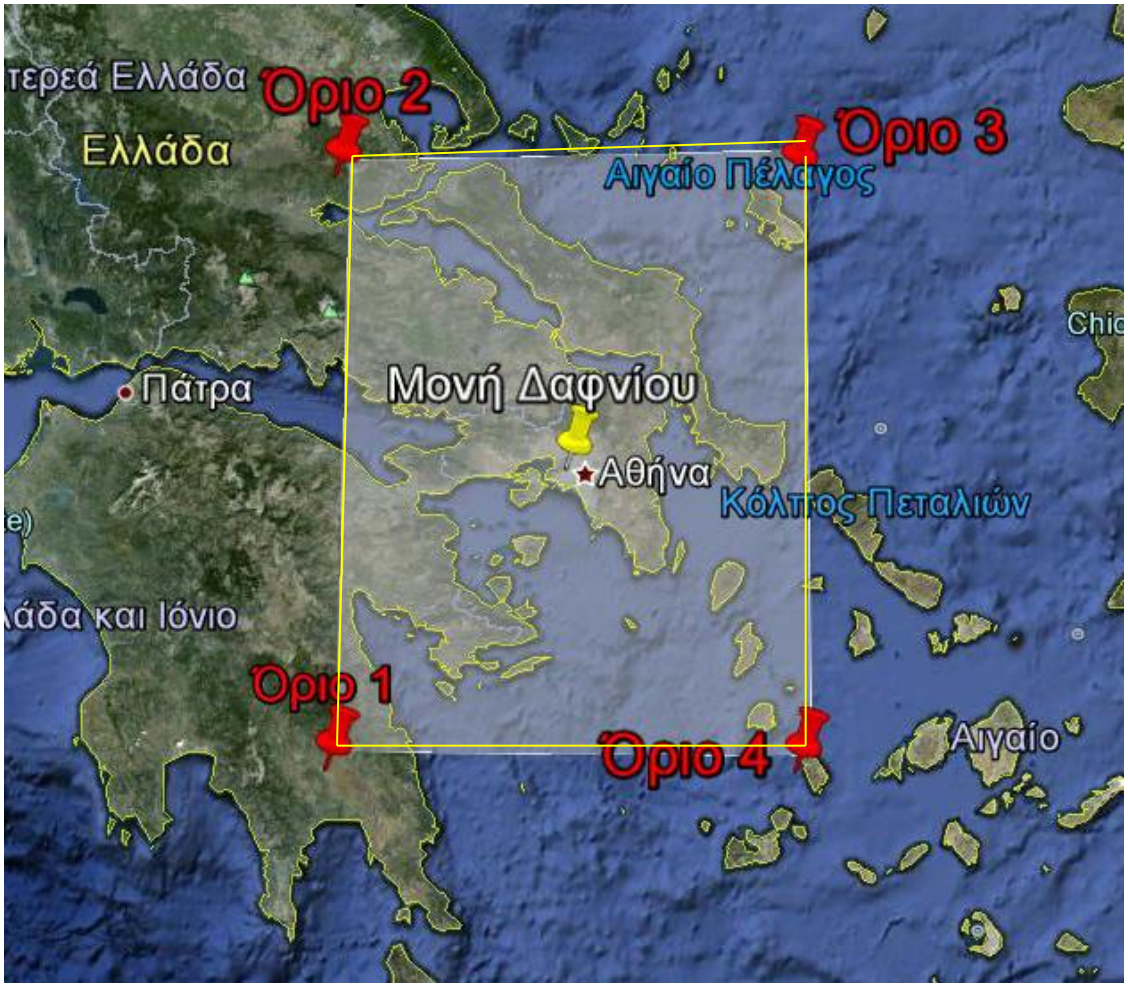
Out-of-plane displacement of 100 years ago reconstructed walls

Comparison between historical and recent pathology:

1. Similar damage
2. Justification of the measures taken (beginning of 20th century)
3. The measures taken up to now were not able to prevent extensive damage

Therefore, further measures should be taken to protect the monument against further severe damage and loss of the mosaics

The seismicity of a broad area is included, in order to take into account the large number of active faults of surrounding regions (e.g. east Corinthian gulf, Boeotia, west Attica) that have affected the monument in the past.



On the basis of the characteristics of the seismic events of the selected regions, in combination with the dynamic characteristics of the monument, the expected peak ground acceleration was estimated (50 years, 10% probability of exceedance) to 0,30g.

MONITORING-DYNAMIC PROPERTIES

Reliable and critical information about the response of the monument to seismic actions, before, during and after the application of interventions

- Equipment for the collection of data during a seismic event
- Data recording through a system installed in situ, as well as at the NTUA
- Evaluation of results

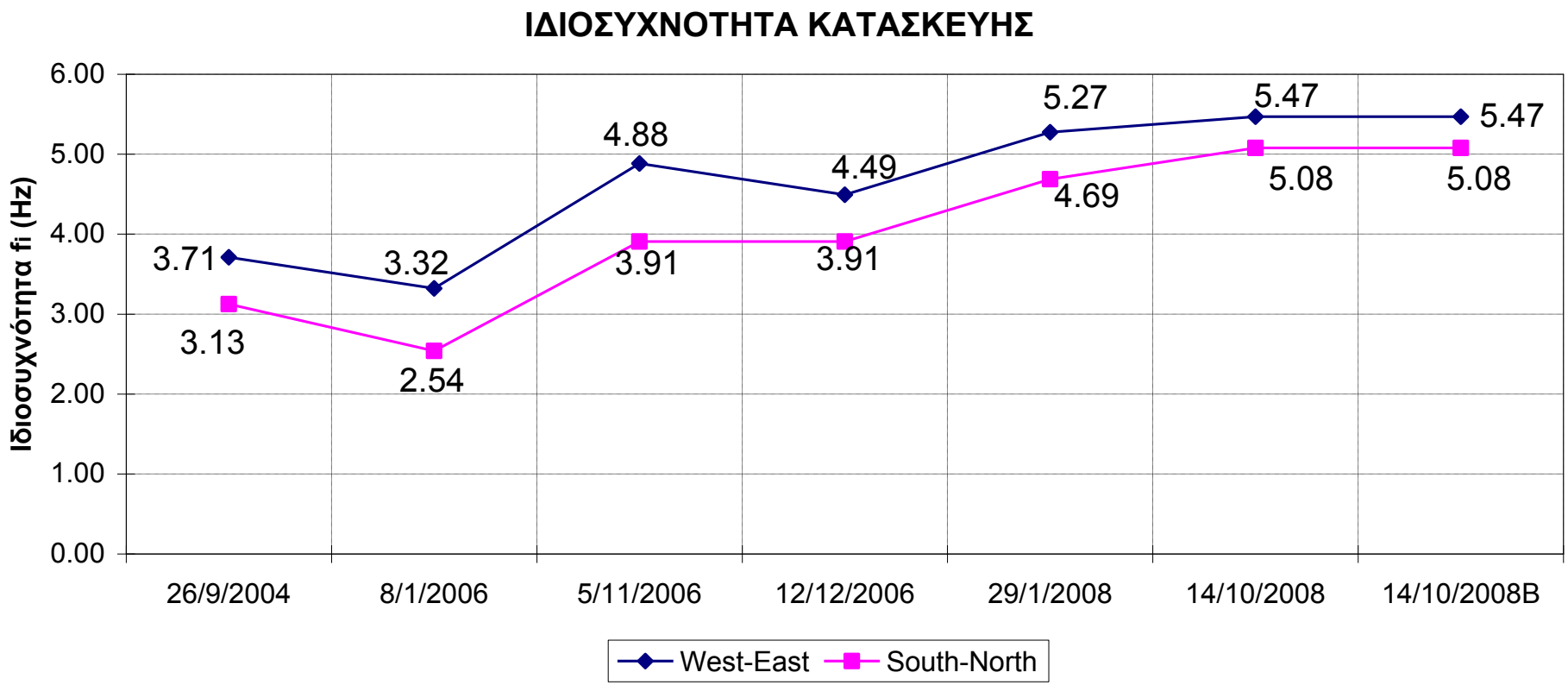
- THE EQUIPMENT
- Accelerometres: Measuring the acceleration due to an earthquake at three levels (interior and exterior of the monument), as well as on the ground.
- Displacement-metres: Measuring displacements in the interior of the monument (at the base of the system of domes and vaults) .

MONITORING-DYNAMIC PROPERTIES

- **Residual deformation along the N-S direction**

- **Increase of the eigenfrequency , reduction of the period of vibration and reduction of the damping, after the application of grouts**

DYNAMIC AMPLIFICATION FACTORS



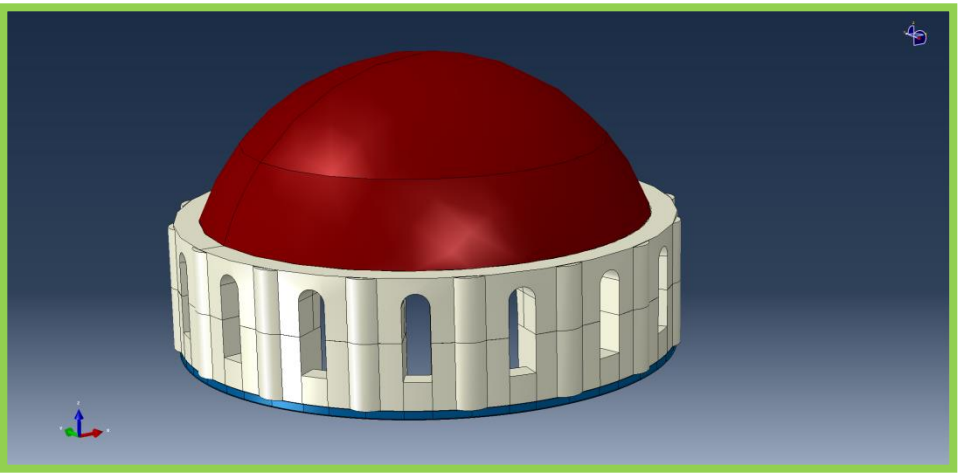
2ND PHASE OF INTERVENTIONS

a) Assessment of the efficiency of interventions through analyses of the behaviour of the monument with and without interventions, using reliable models calibrated on the basis of the results of the monitoring system, as well as on their ability to “reproduce” the current pathology of the monument.

b) Design of interventions, after in-situ check of their applicability, taking into account the actual geometry of various parts of the monument and, of course, the locations of mosaics that must be protected.

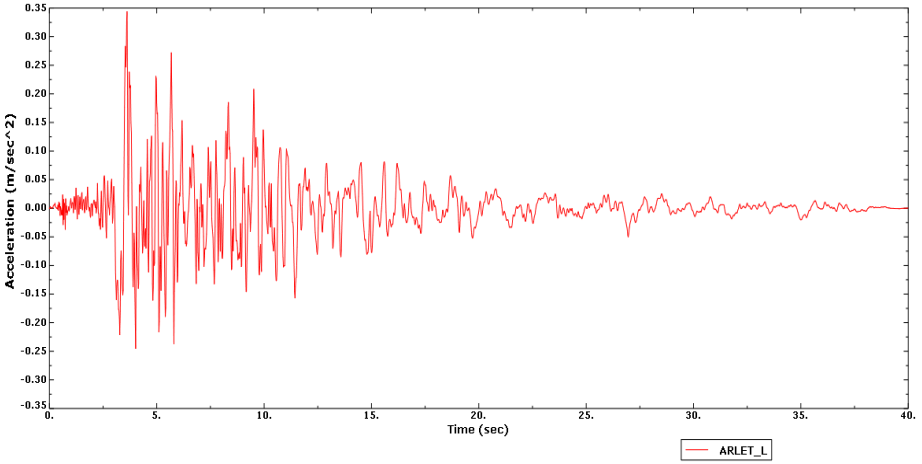
c) All 3D drawings that are necessary for the proposed interventions to be identified, as well as adequate plans and sections, so that the possibility of applying hidden and visible interventions be fully documented. The effects of the interventions on the appearance of the monument should also be fully documented.

THE DOME



Equivalent static analysis

THE ENTIRE MONUMENT



Equivalent static analysis

and
Time-history analyses

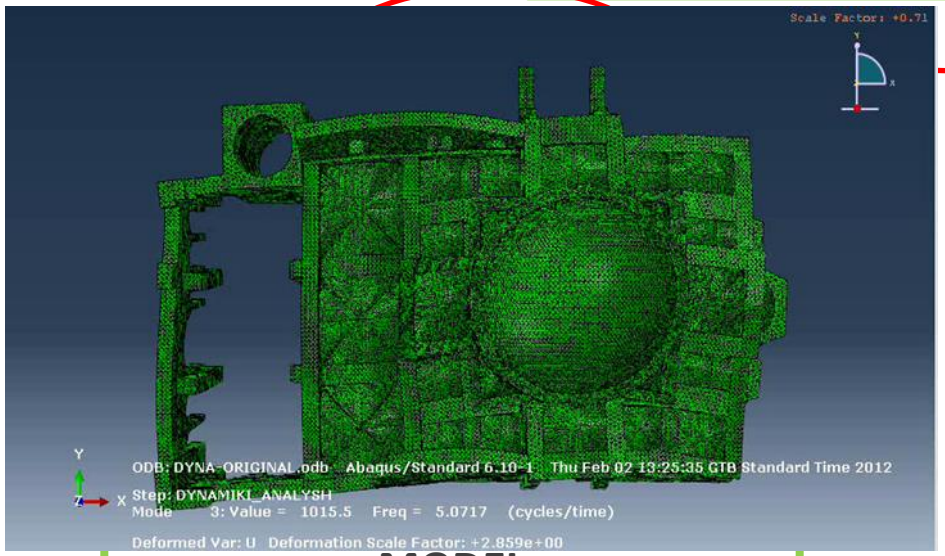
CALIBRATION OF MODELS

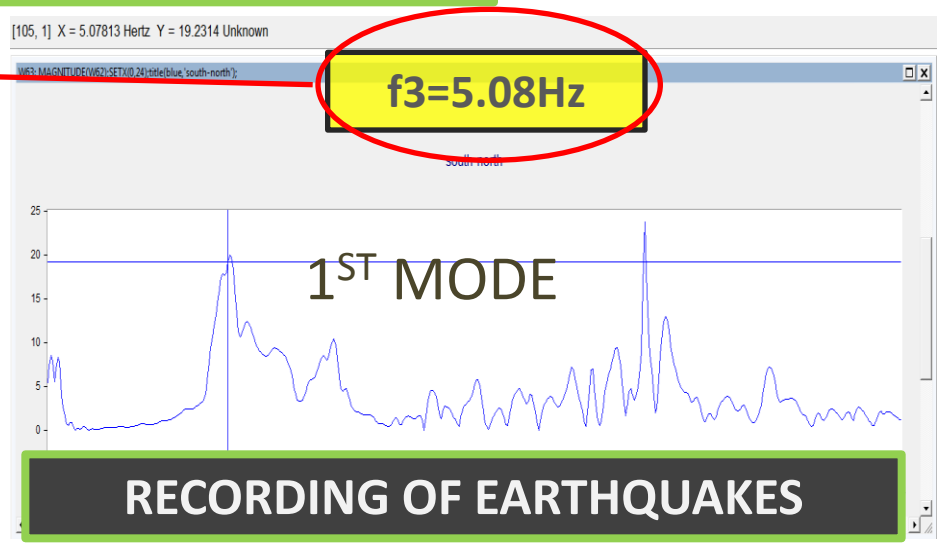
MONITORING SYSTEM

THE DATA WERE USED FOR THE CALIBRATION OF THE MODELS

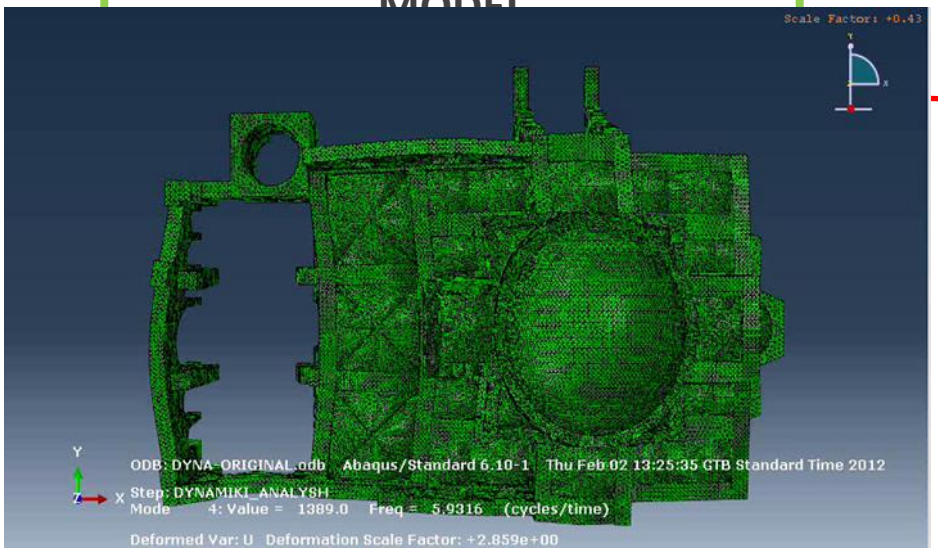
CALIBRATION OF MODELS

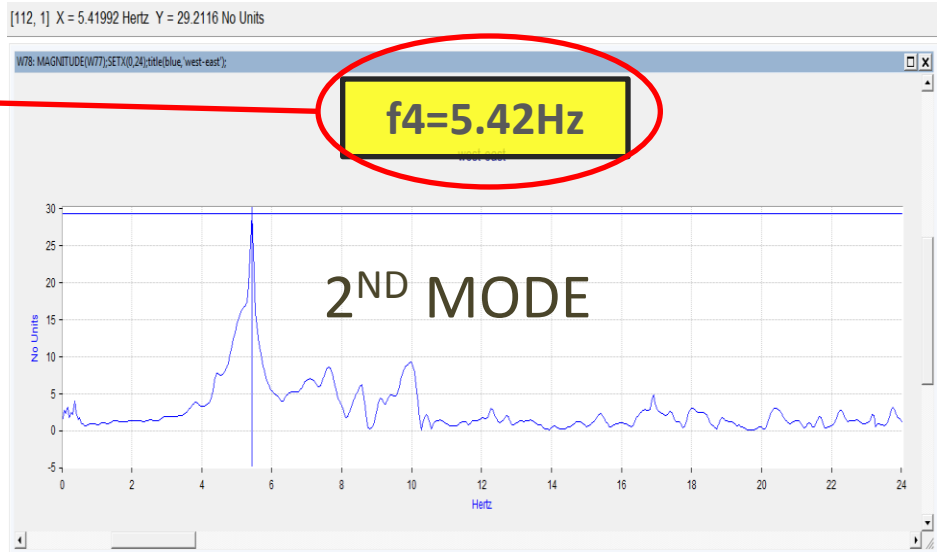
EIGEN-FREQUENCIES





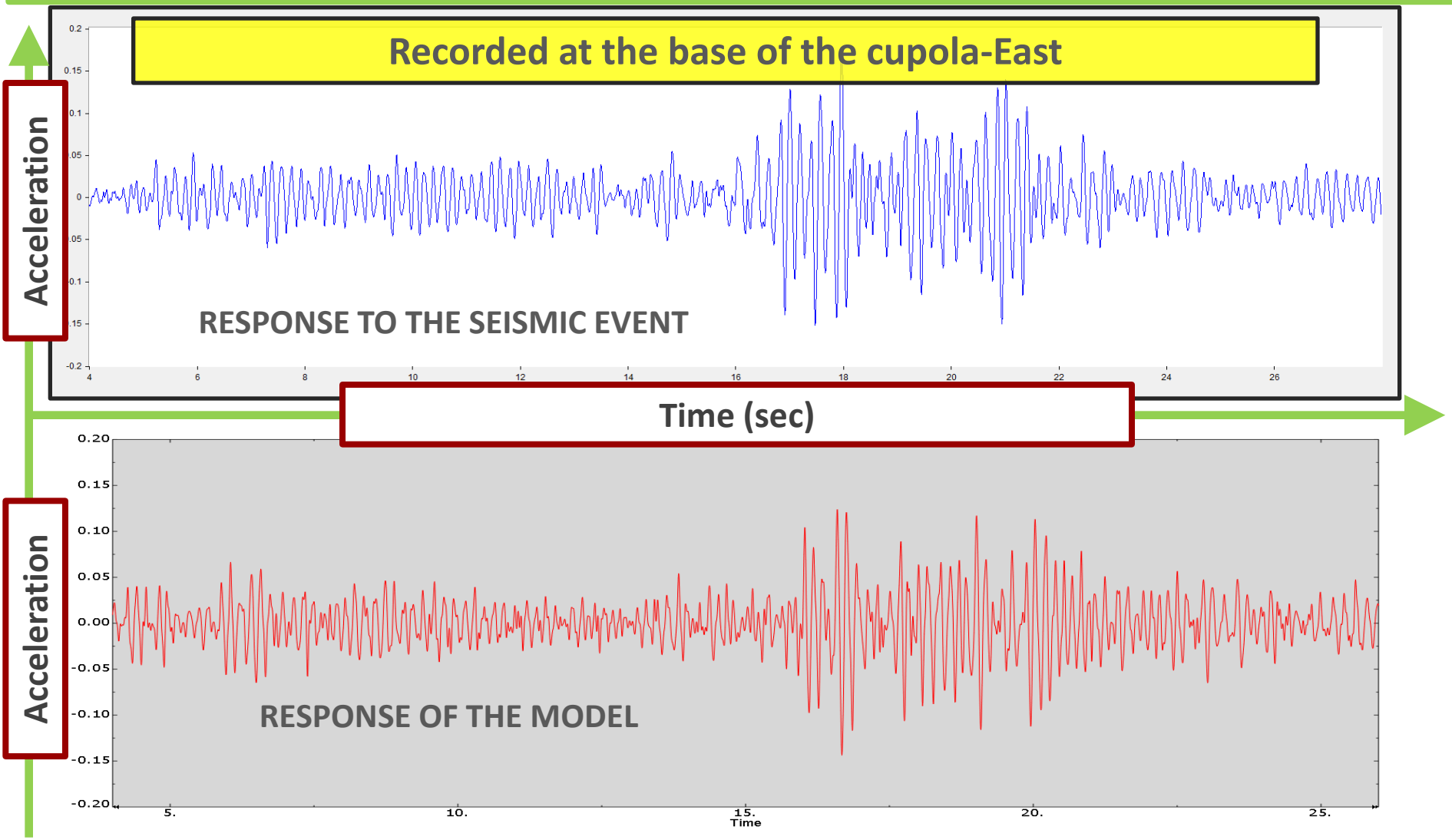
MODEL



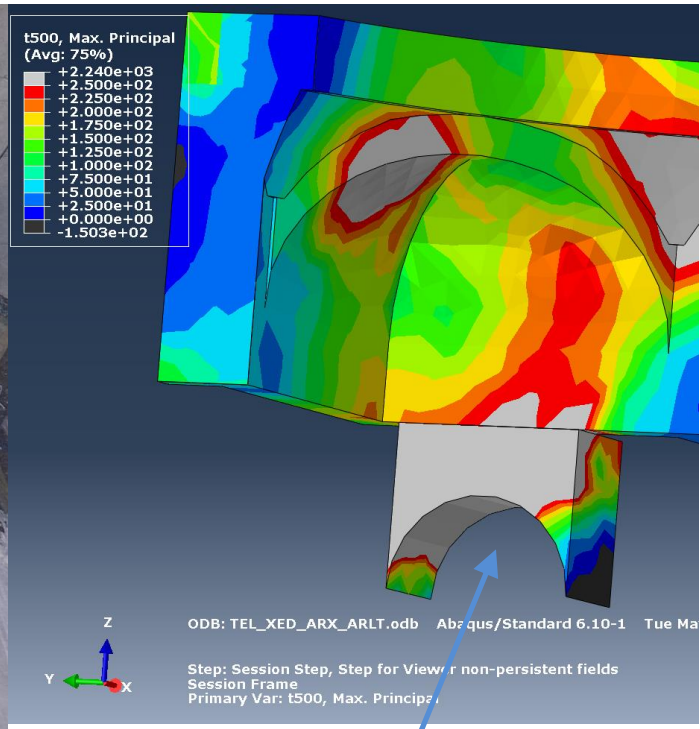


CALIBRATION OF MODELS

COMPARISON WITH ACCEL. MEASURED DURING EARTHQUAKES 4/10/08, 02/09/09

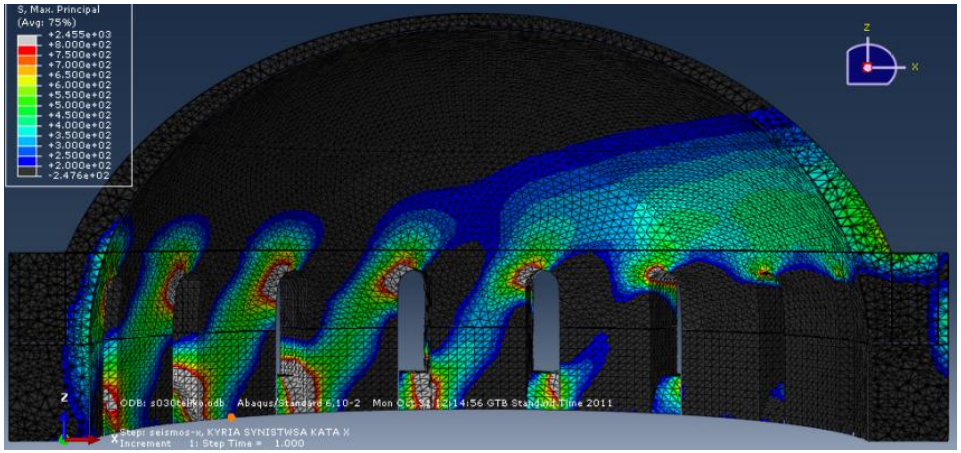


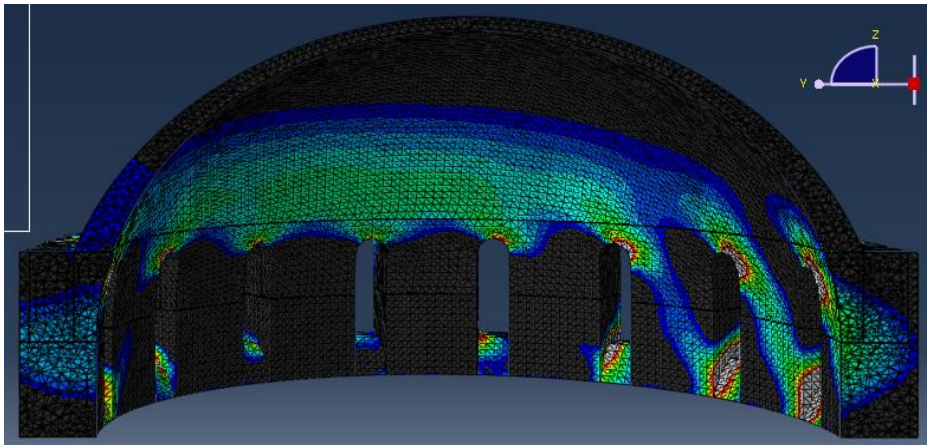
REPRODUCTION OF OBSERVED DAMAGES-PENDATIVES-ARCHES

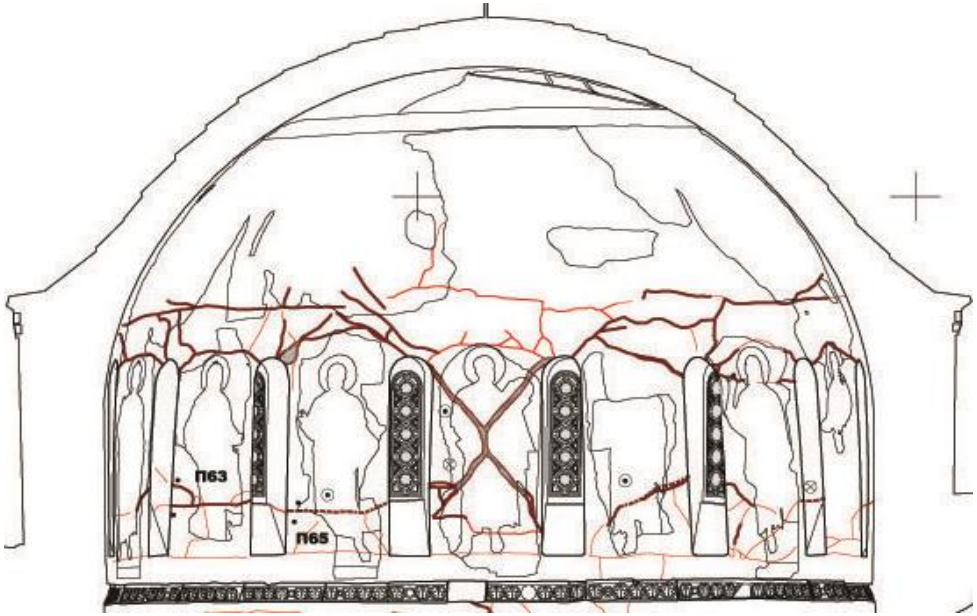


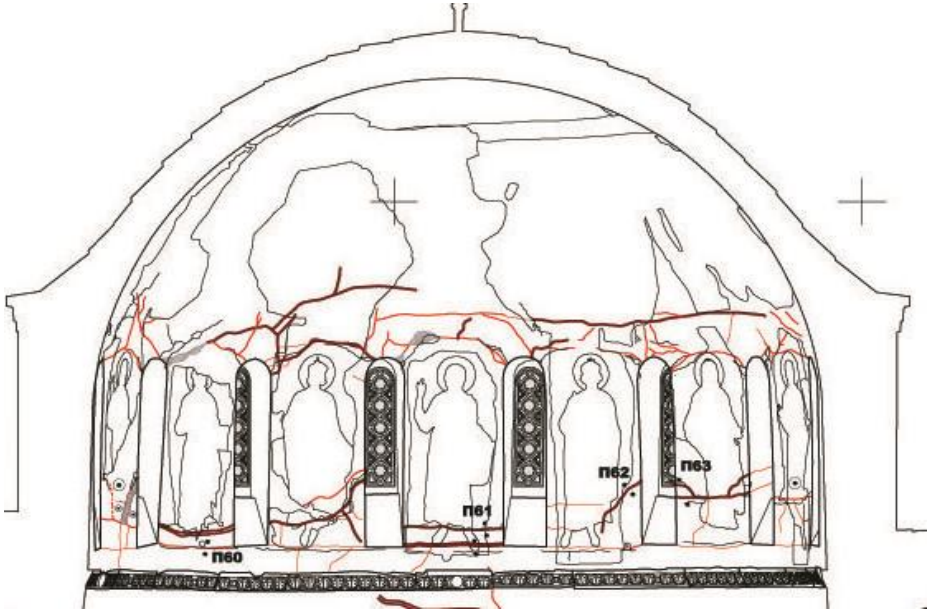
MAXIMUM TENSILE STRESSES FOR THE BEARING SYSTEM BEFORE INTERVENTIONS

REPRODUCTION OF OBSERVED DAMAGES-DOME

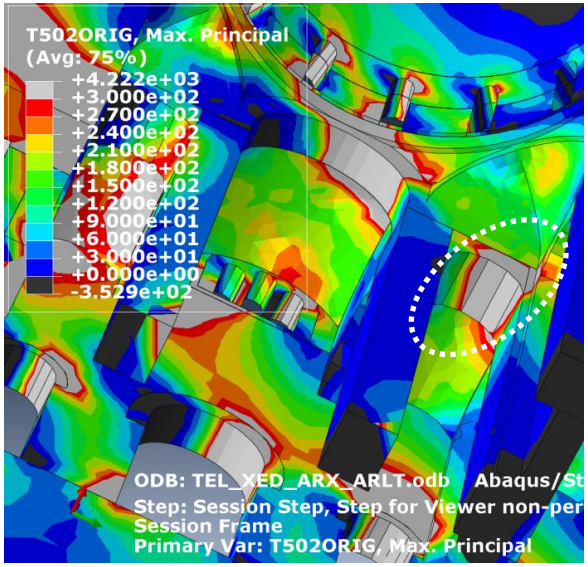


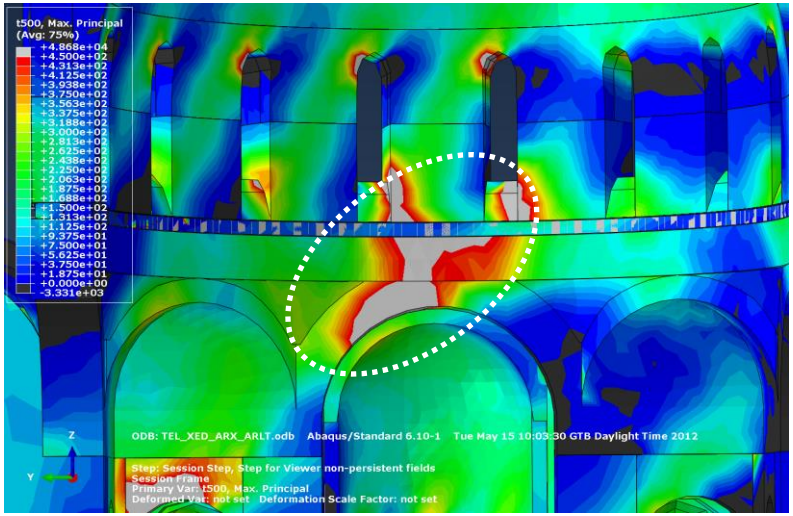






REPRODUCTION OF OBSERVED DAMAGES





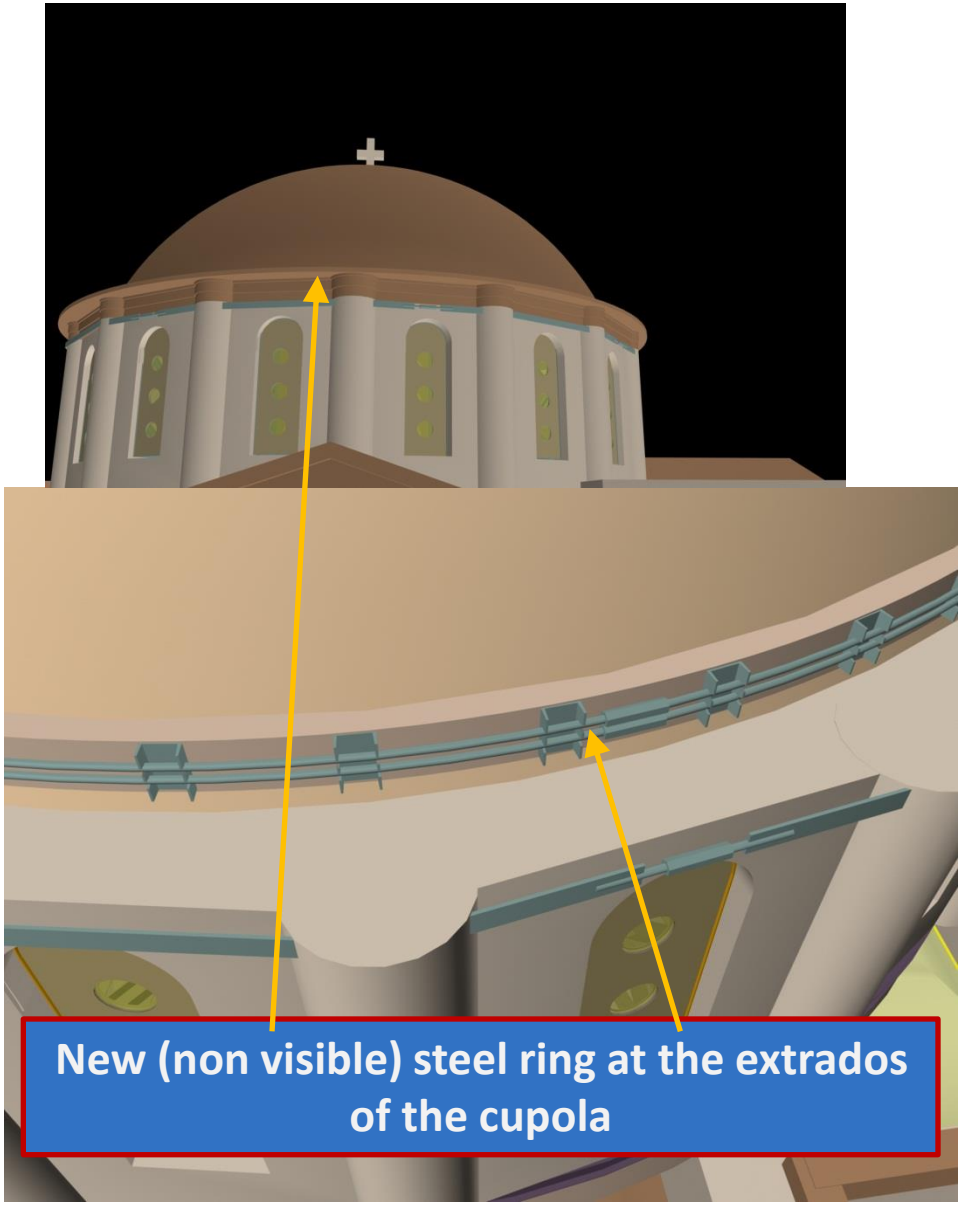
ASSESSMENT OF THE EFFICIENCY OF ALTERNATIVE STRENGTHENING MEASURES

Calibration and check of the models

- Comparison with data obtained through the monitoring system
- Analytical re-production of the pathology
- Confirmation of the vulnerability of the monument

Thus, the models could be considered as reliable and used for the assessment of the efficiency of alternative intervention measures and for the selection of the optimal intervention scheme.

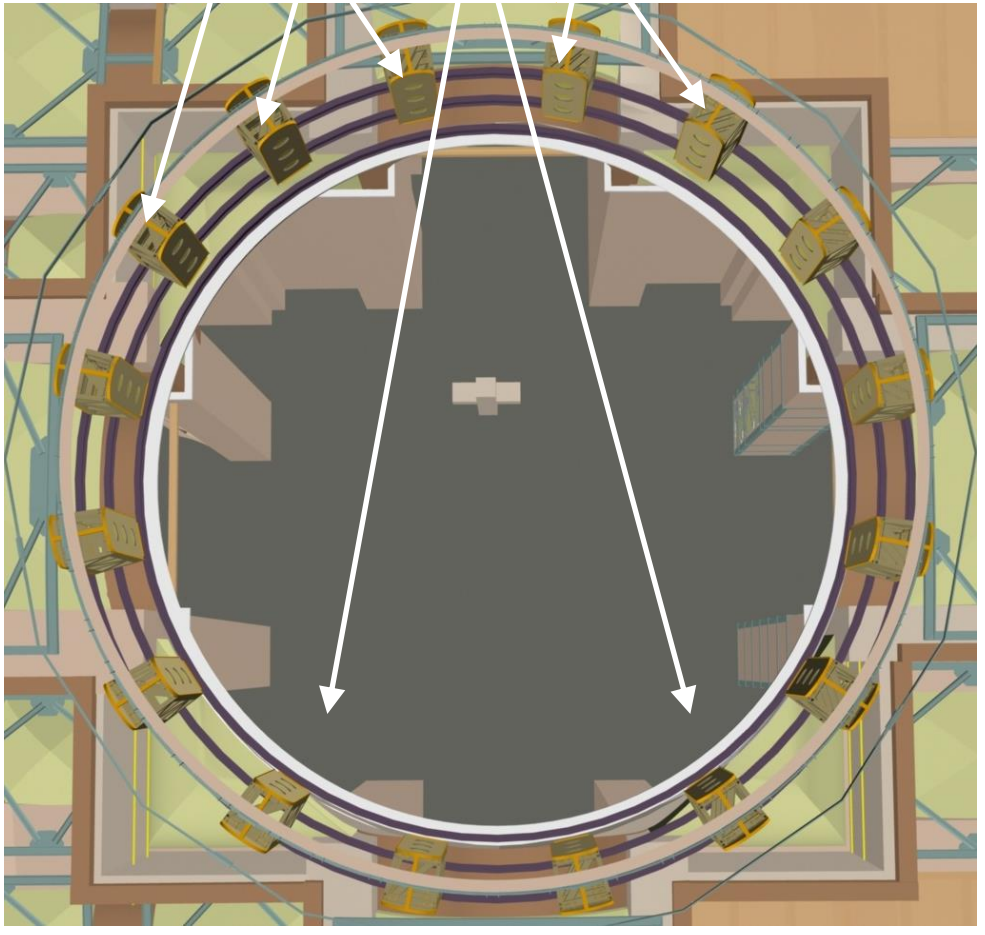
INTERVENTIONS



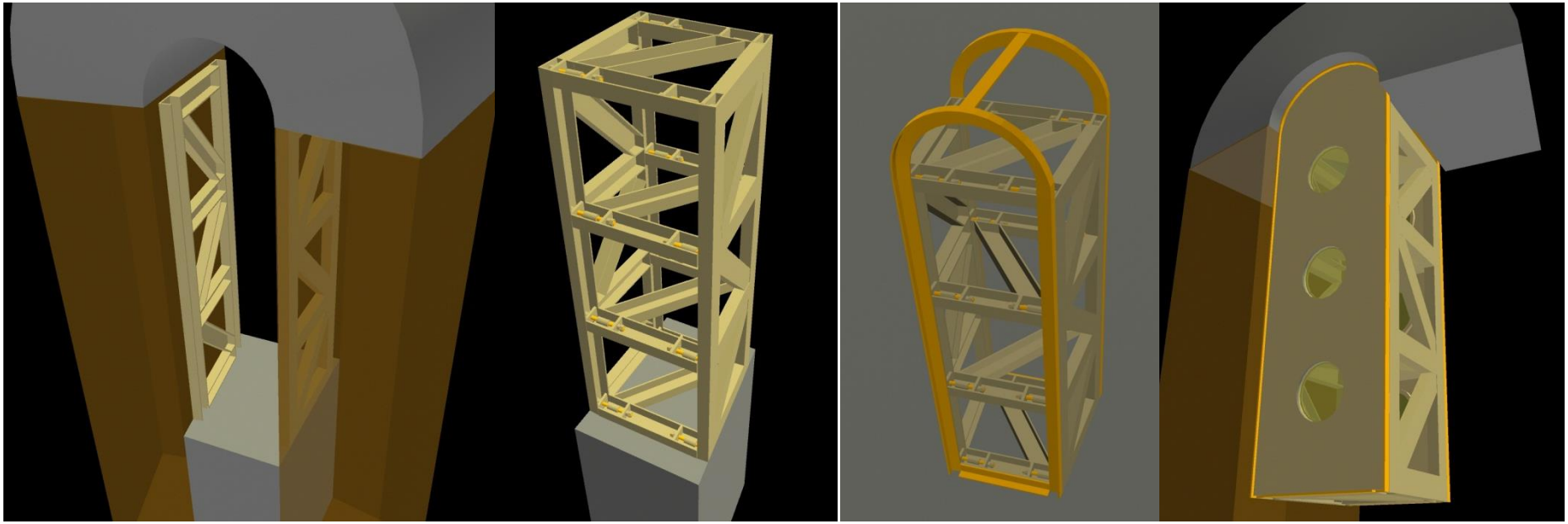
INTERVENTIONS

Removal of immediate protective measures

New steel stiffening frames in the openings of the drum

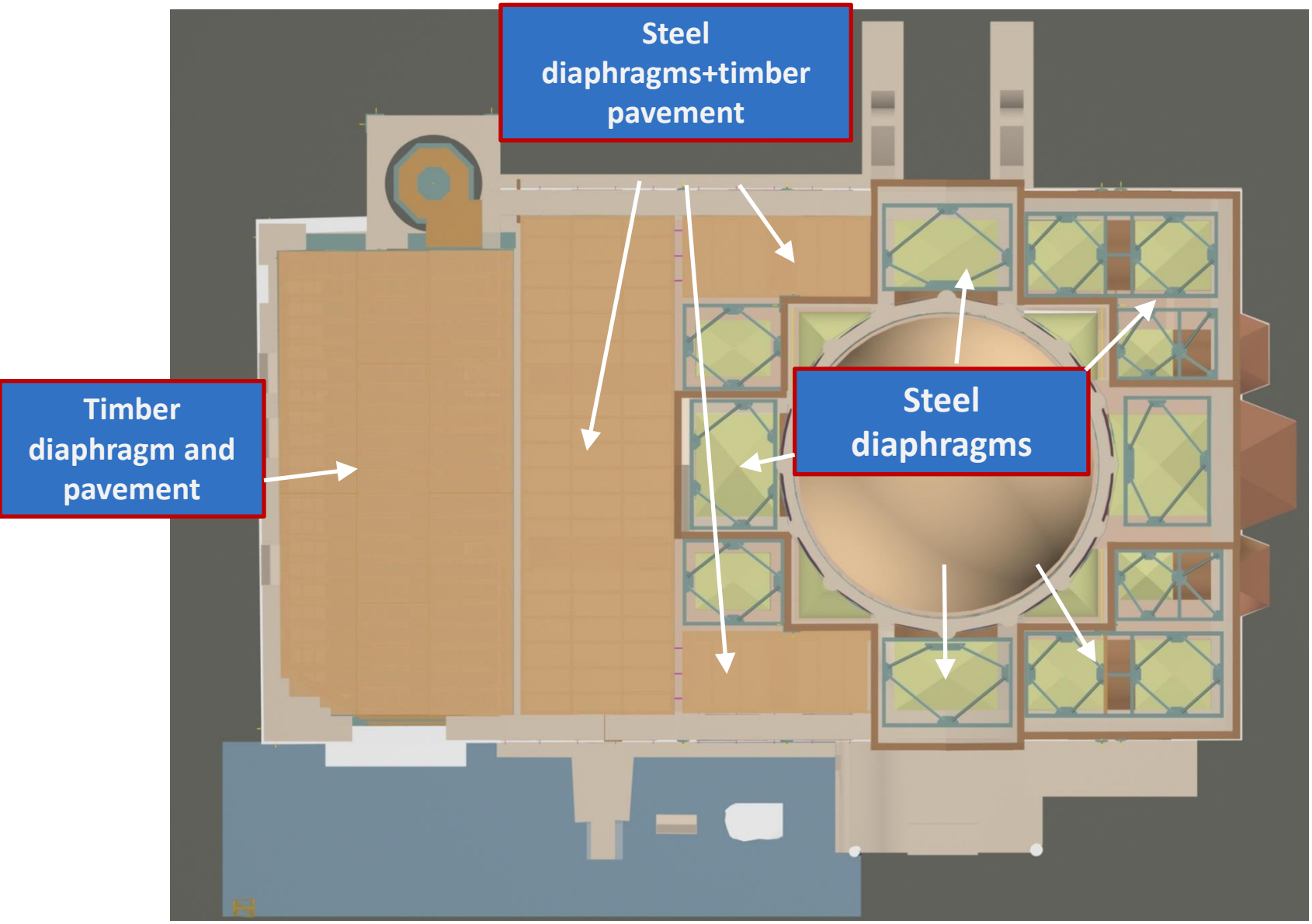


Steps of the construction of the stiffening frames



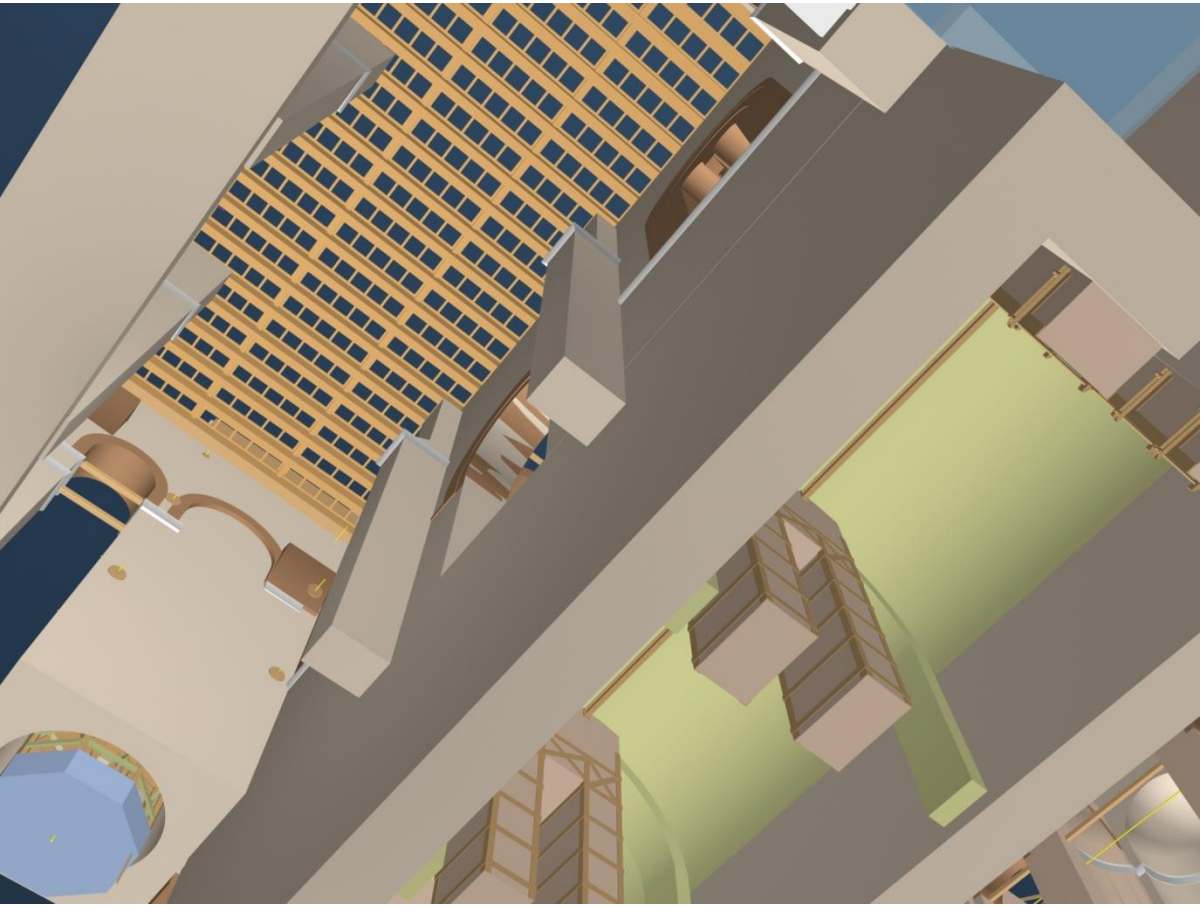
Diaphragms at the extrados of domes and vaults & diaphragm at the exo-narthex

INTERVENTIONS



INTERVENTIONS

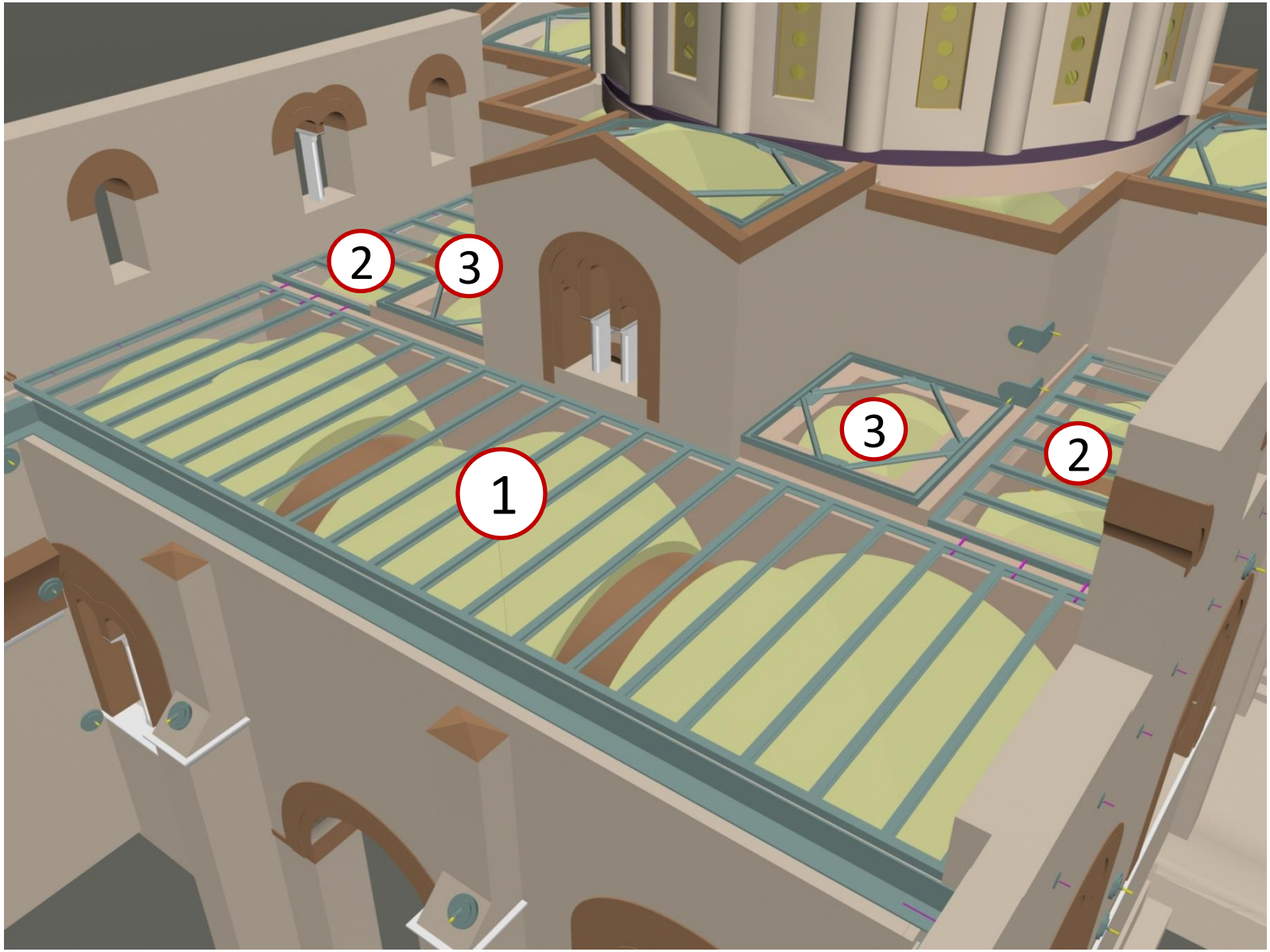
Diaphragm at the western part



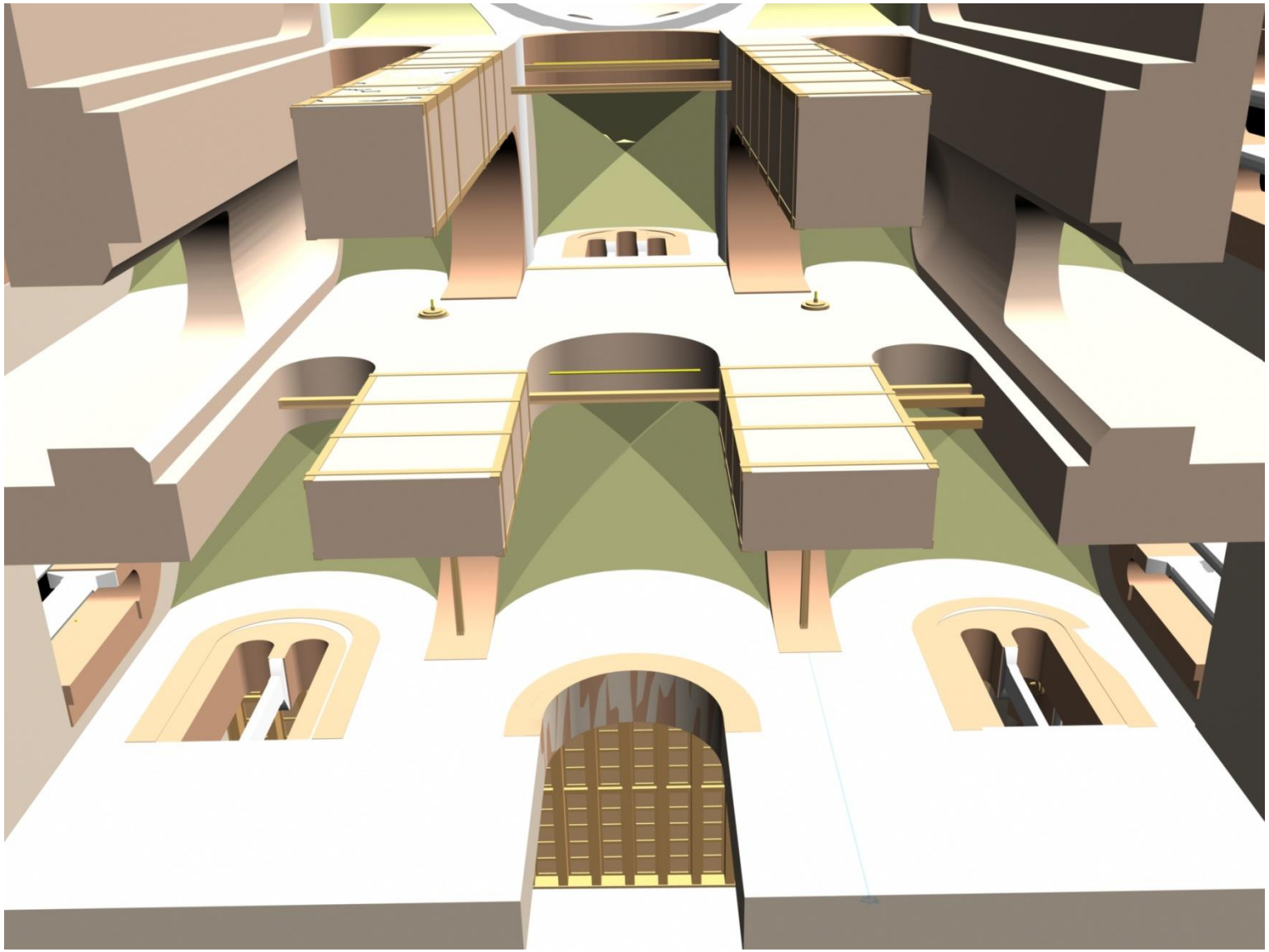
Timber floor and pavement

Steel diaphragms with timber pavement or without pavement

INTERVENTIONS



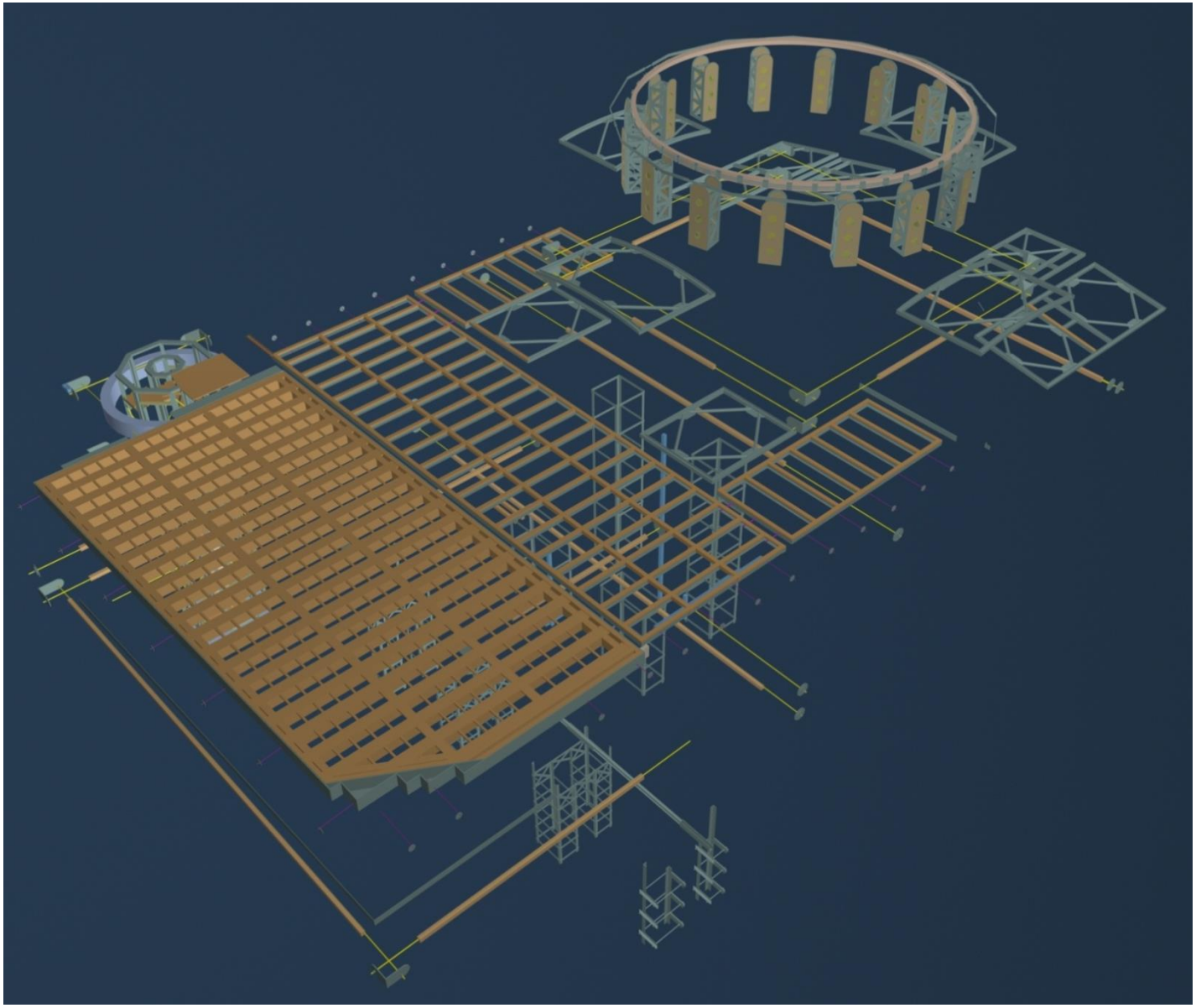
Ties/Struts-Narthex



“Confinement” of piers

INTERVENTIONS

INTERVENTIONS



MOST OF THEM-INVISIBLE

View of the monument after intervention

INTERVENTIONS

ASSESSMENT OF THE EFFICIENCY OF ALTERNATIVE STRENGTHENING MEASURES

METHODOLOGY

Each intervention measure was studied separately, whereas alternatives were also considered (regarding the form and the location of application of each measure).

For this purpose, the bearing system was analyzed at its cracked state, where this was necessary for the efficiency of the measures to be checked (for example, ties),

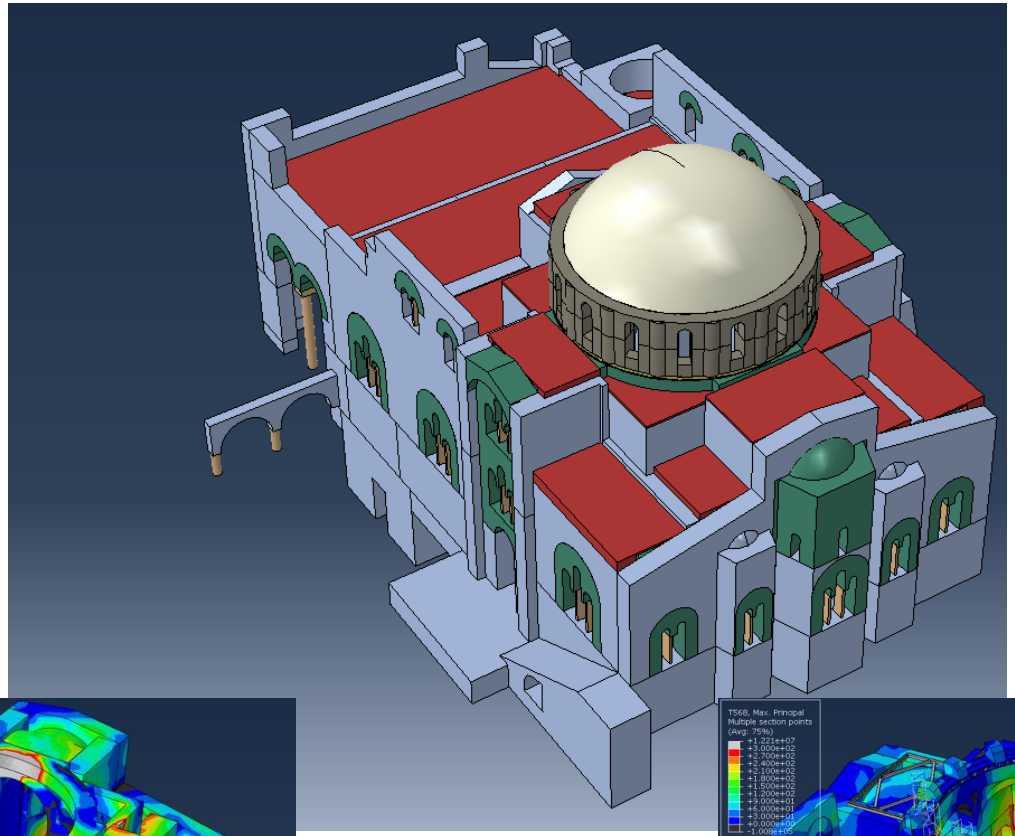
The best performing measures were, then, considered all together and the behaviour of the monument was assessed.

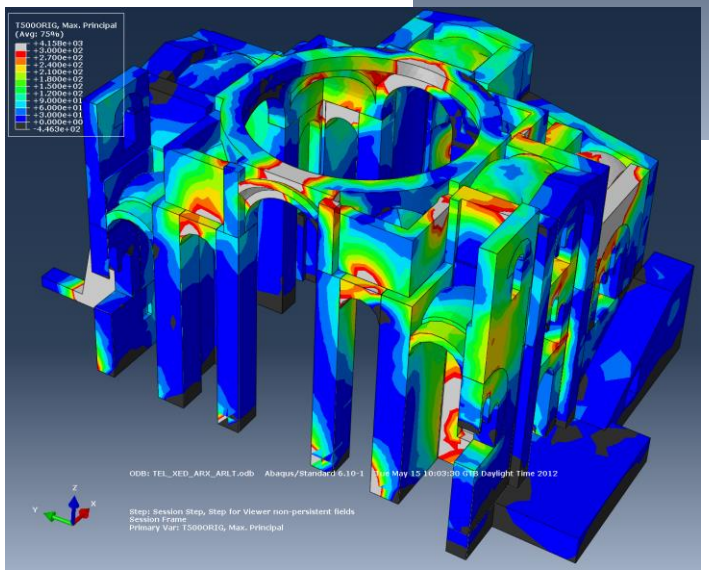
SELECTION OF OPTIMAL INTERVENTIONS

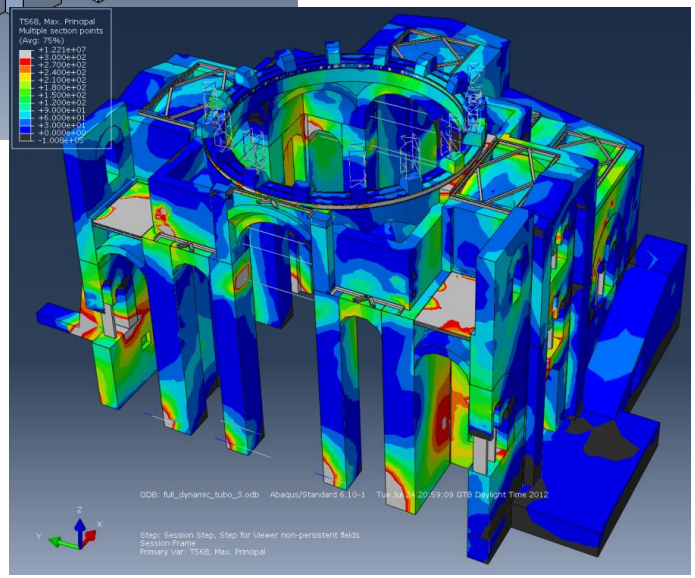
That are absolutely necessary for the improvement of the seismic behaviour of the monument, **taking into account the values of the monument.**

It should be noted that, even after the application of the strengthening measures, the occurrence of damages due to a strong earthquake **are NOT excluded.**

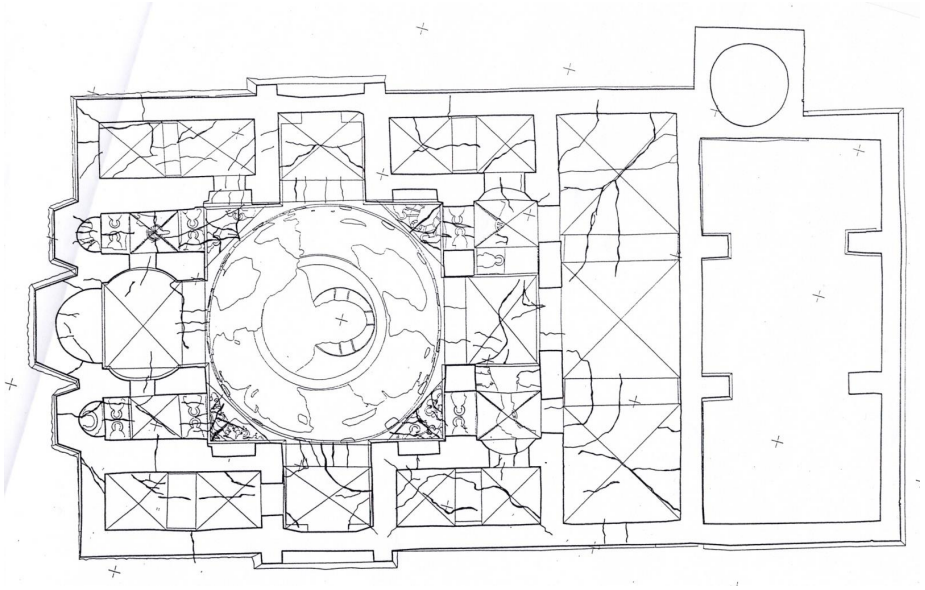
ASSESSMENT OF EFFICIENCY OF ALL INTERVENTION MEASURES ON THE ENTIRE BUILDING

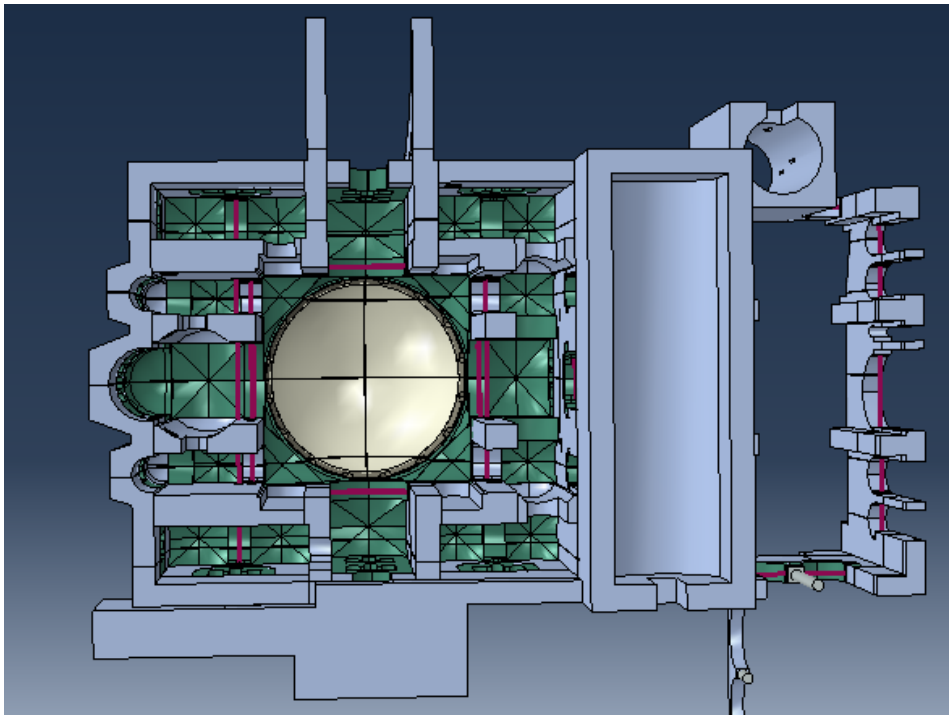






Struts and ties/Cracked state





Dimensioning of ties

2nd phase interventions: improving the overall behaviour

Confinement of the dome at two levels, installation of stiffening frames in the windows of the drum and construction of metallic diaphragms at the extrados of the groin vaults.

2nd phase interventions: improving the overall behaviour

Construction of diaphragms: exo-narthex and extrados of the vaults of the narthex.

2nd phase interventions: improving the overall behaviour

IC
XC