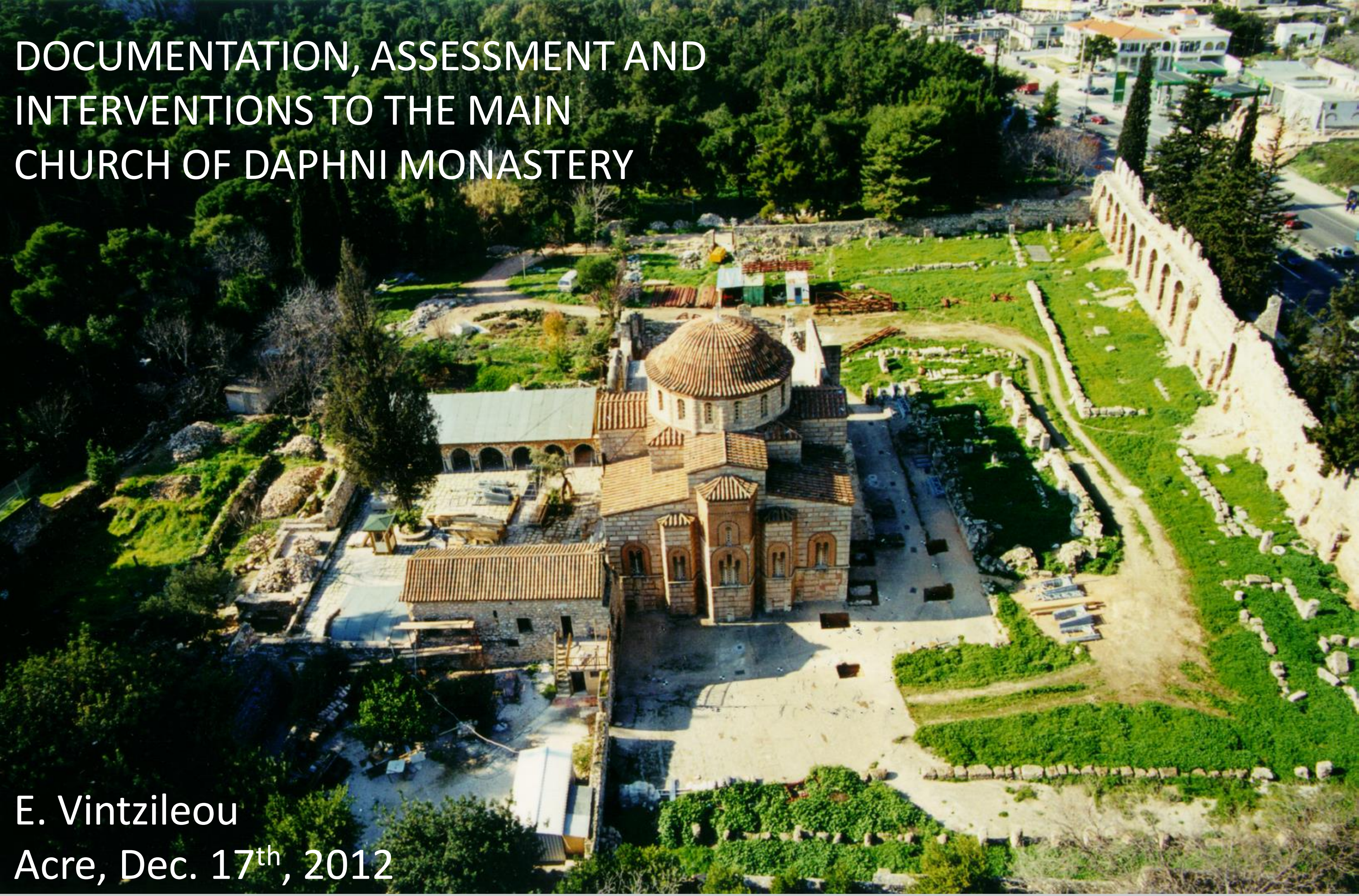
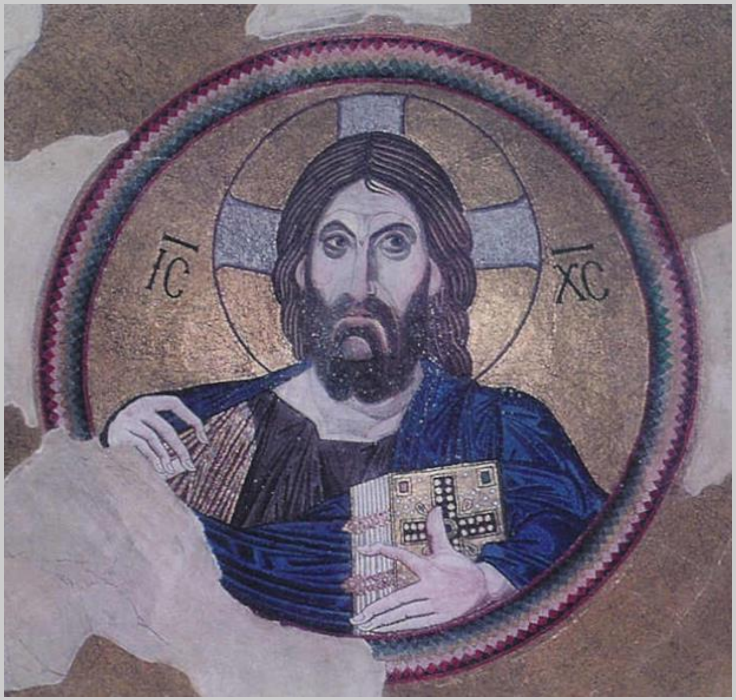
DOCUMENTATION, ASSESSMENT AND INTERVENTIONS TO THE MAIN CHURCH OF DAPHNI MONASTERY



E. Vintzileou

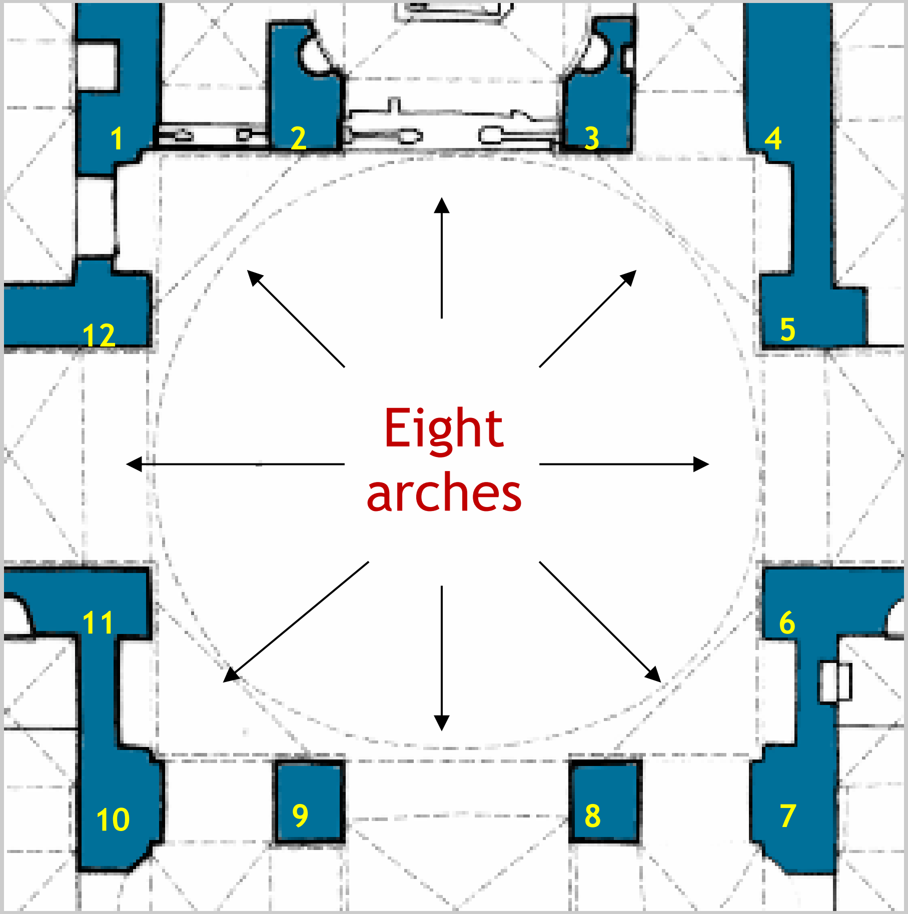
Acre, Dec. 17th, 2012

The Dafni Monastery (built in the 11th century) is one of the most important byzantine monuments in Greece (mainly because of the mosaics of the Katholikon, (UNESCO-list of world monuments)).



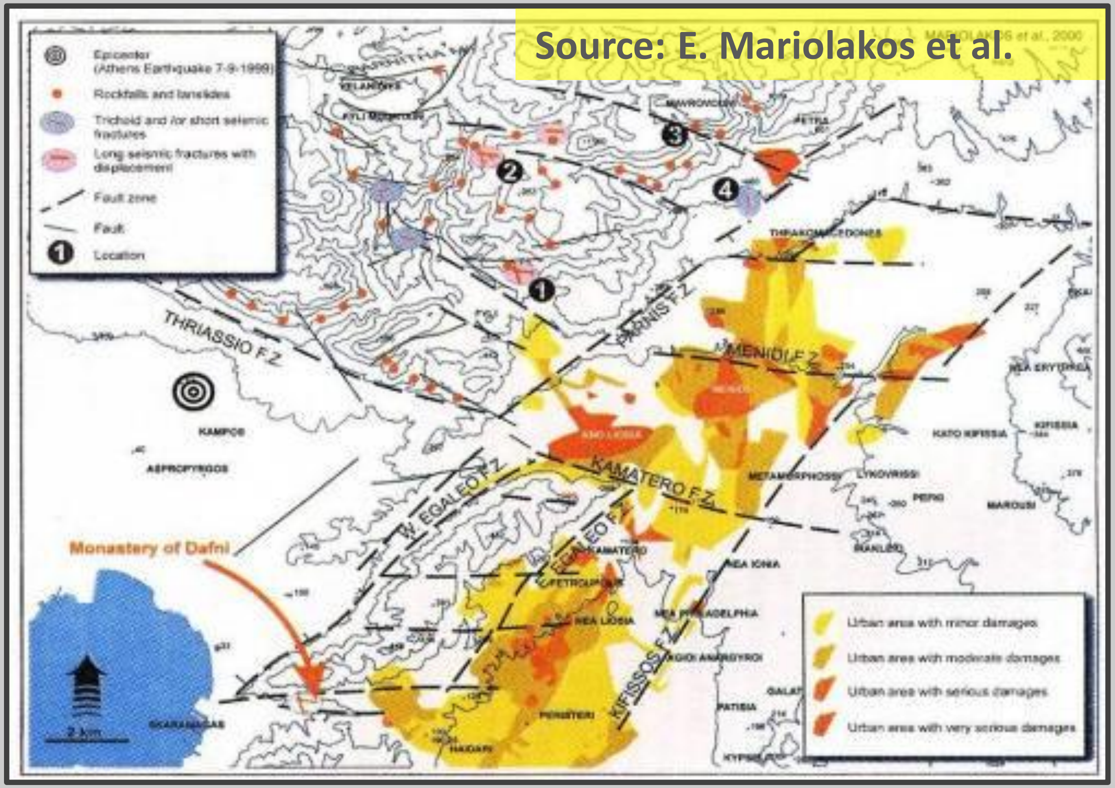
THE TYPOLOGY OF THE KATHOLIKON

Octagonal



Twelve piers (forming a square plan) and the pendatives support the dome.

THE MONUMENT IS CONSTRUCTED IN A HIGHLY SEISMIC AREA



Source: E. Mariolakos et al.

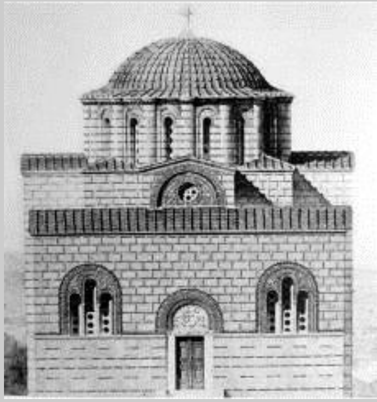
A monument that has sustained many damages and numerous interventions

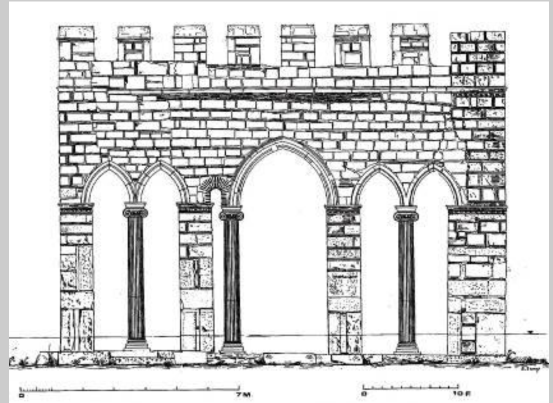
DOCUMENTED: Historical pathology

Earthquakes (Ms>6) that have affected the Monastery

Year	Ms	Location
1837	6,2	Hydra
1853	6,8	Thiva
1858	6,7	Corinth
1876	6,1	Corinth
1887	6,3	Corinth
1891	6,3	Kythnos
1894	7,0	Athens
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	Athens

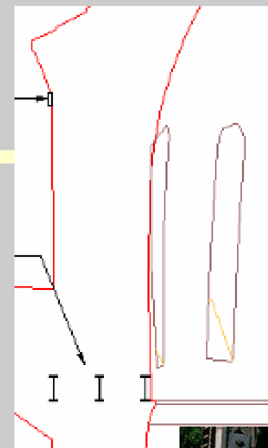
CONSTRUCTION PHASES- HISTORICAL PATHOLOGY AND MORE RECENT INTERVENTIONS



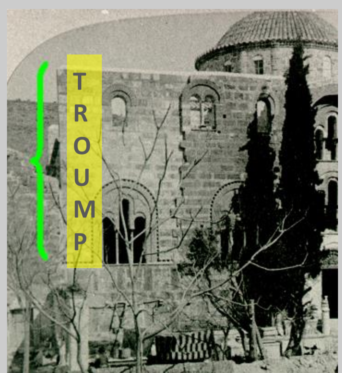


Three construction phases

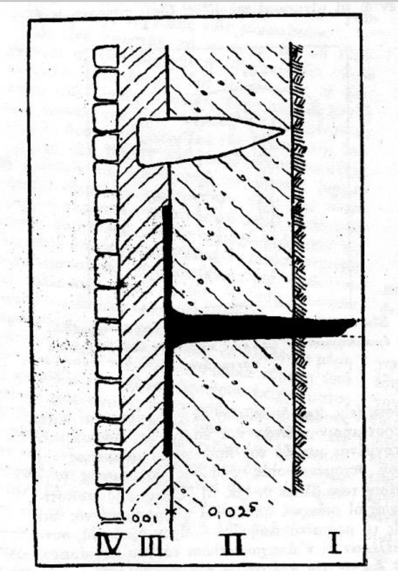
Original New dome



1890-1891 Demolition of the original dome (criticism)



HISTORICAL PATHOLOGY AND MORE RECENT INTERVENTIONS



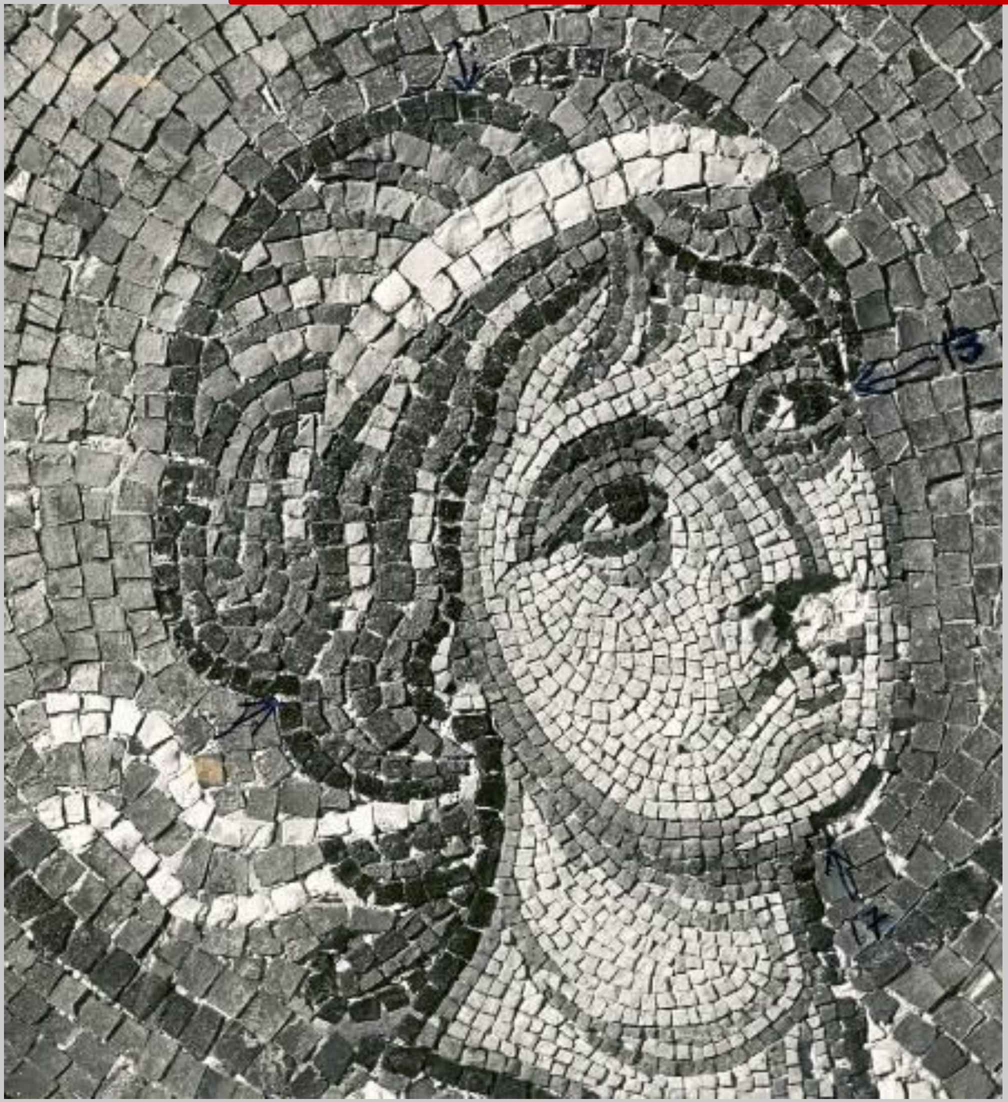
Εἰκ. 3. Κονιάματα καὶ σύνδεσμοι τούτων διὰ σιδηρῶν ἥλων καὶ ψηφίδων εἰς σχῆμα σφηνῶν (Ι τοῖχος, ΙΙ α' κονίαμα, ΙΙΙ β' κονίαμα, IV μωσαϊκόν).

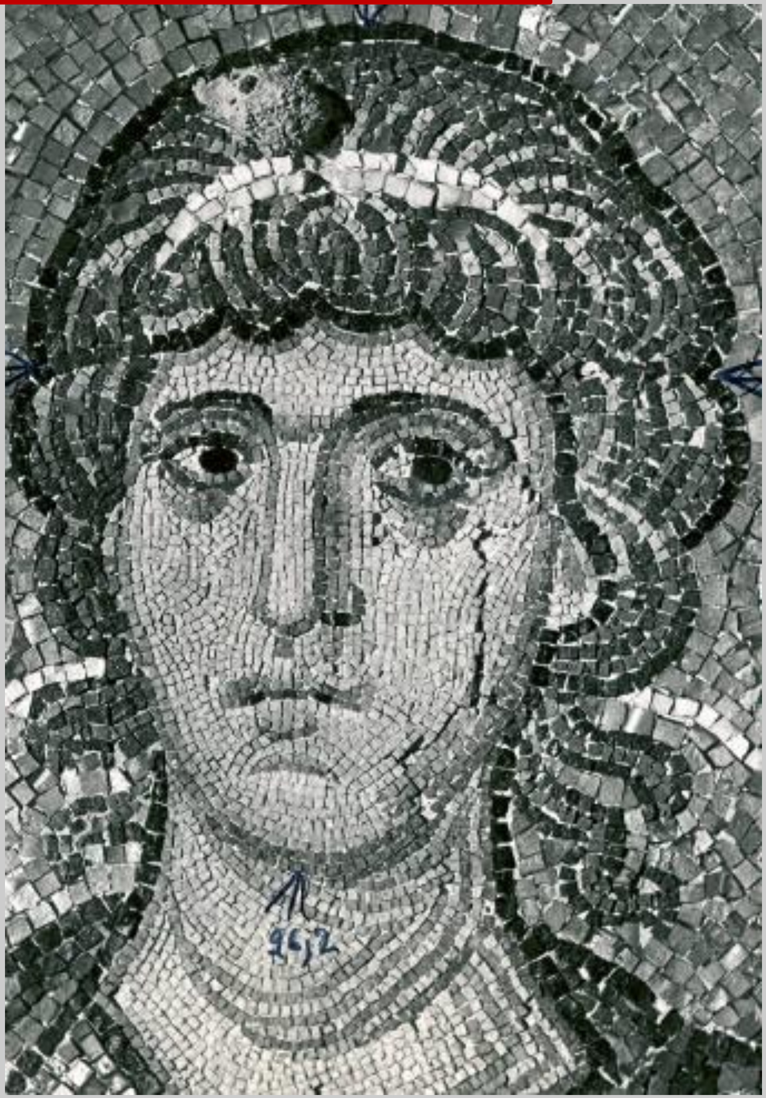
Removal and replacement of mosaics by Italian conservators (NOVO, 1890-1897). Use of hydraulic lime

Use of cement in the more recent interventions

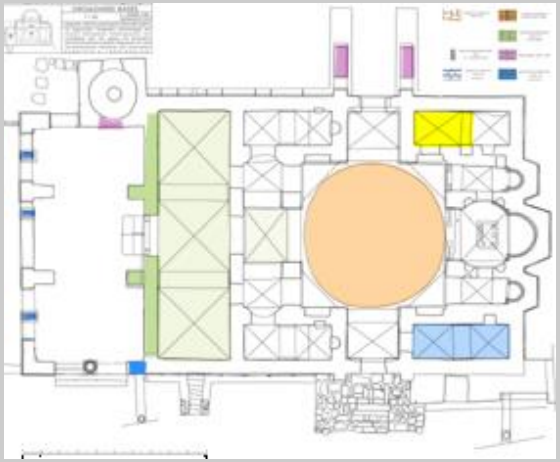
HISTORICAL PATHOLOGY AND MORE RECENT INTERVENTIONS

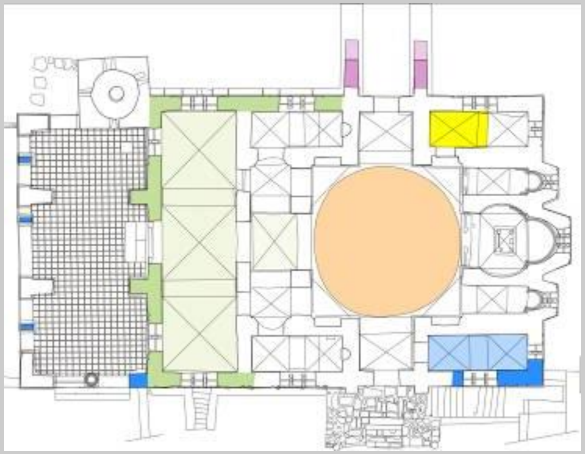
Rather minor damages to the mosaics due to the 1981 earthquake-No measures were taken

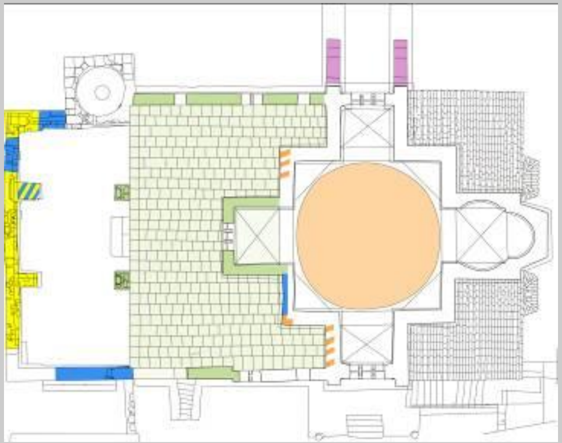


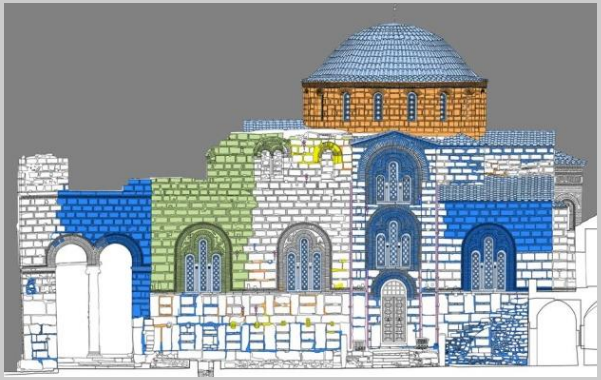


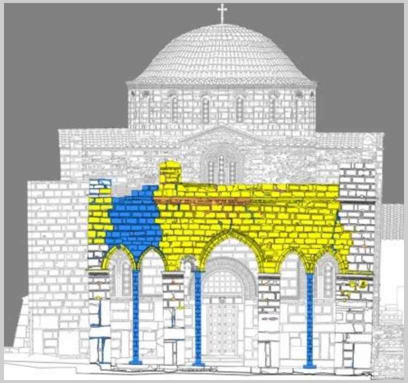
HISTORICAL PATHOLOGY

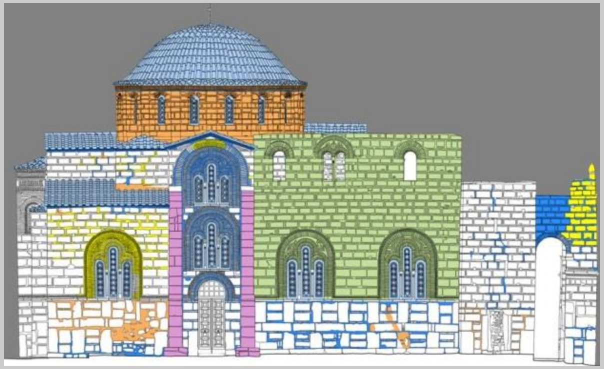


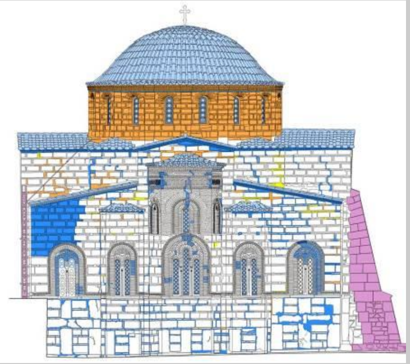










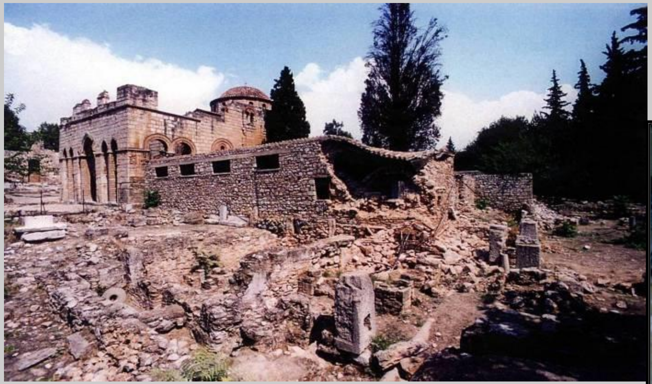


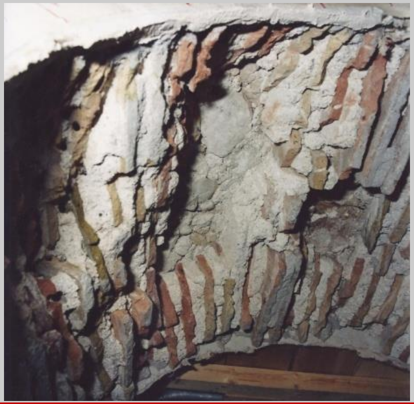
The coloured parts are reconstructed.

RECENT PATHOLOGY AFTER THE 1999 EARTHQUAKE

- Catholikon
- Cells
- Walls
- Auxiliary buildings

Earthquake of September 7th, 1999 → **Severe damages**

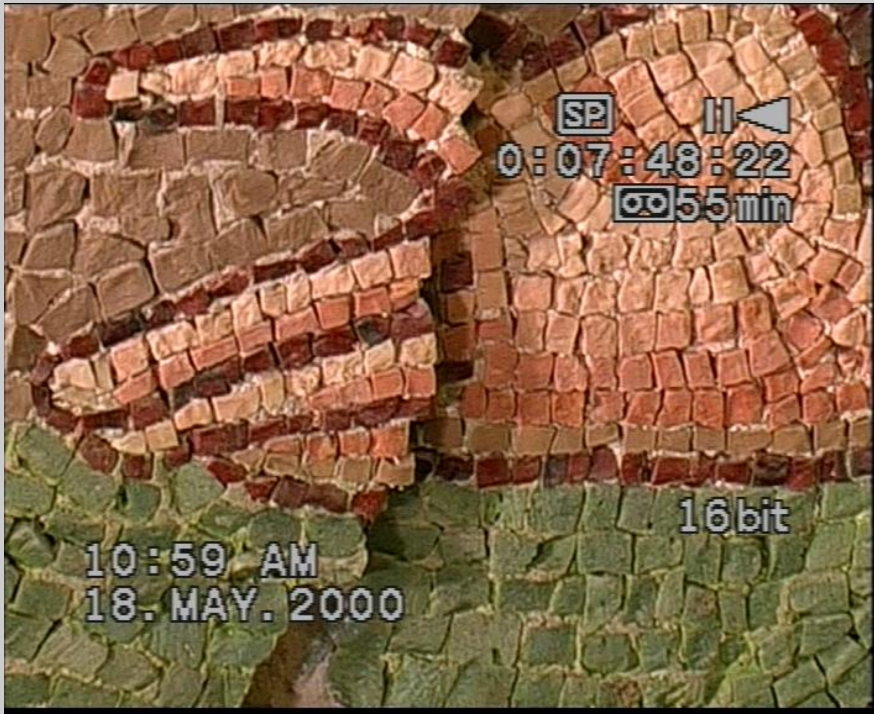




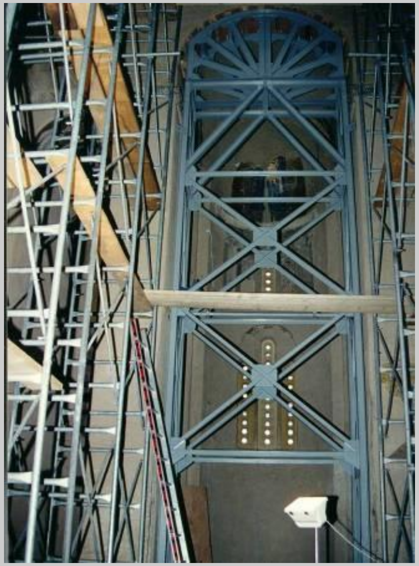
Numerous inlays were covering the pavement. They were collected systematically and nets were placed under each mosaic as a first protective measure (to avoid losses).

RECENT PATHOLOGY AFTER THE 1999 EARTHQUAKE

Severe damages in the mosaics, even in locations where masonry was not cracked



IMMEDIATE PROTECTIVE MEASURES: BUTTRESSES, SHORING, …



The Ministry of Culture has organized and co-funded (with EU) a large scale programme for the exhaustive documentation of the monument to serve the final purpose of repair and strengthening of the monument.

(a) Ministry of Culture: Archaeological data, historical pathology, recognition of the various phases and previous interventions to the monument.

(b) Geophysical methods (identification of ruins in foundation level)-Univ. of Patras

(c) Installation of monitoring system-Geodynamic Institute of Athens and LEE/NTUA

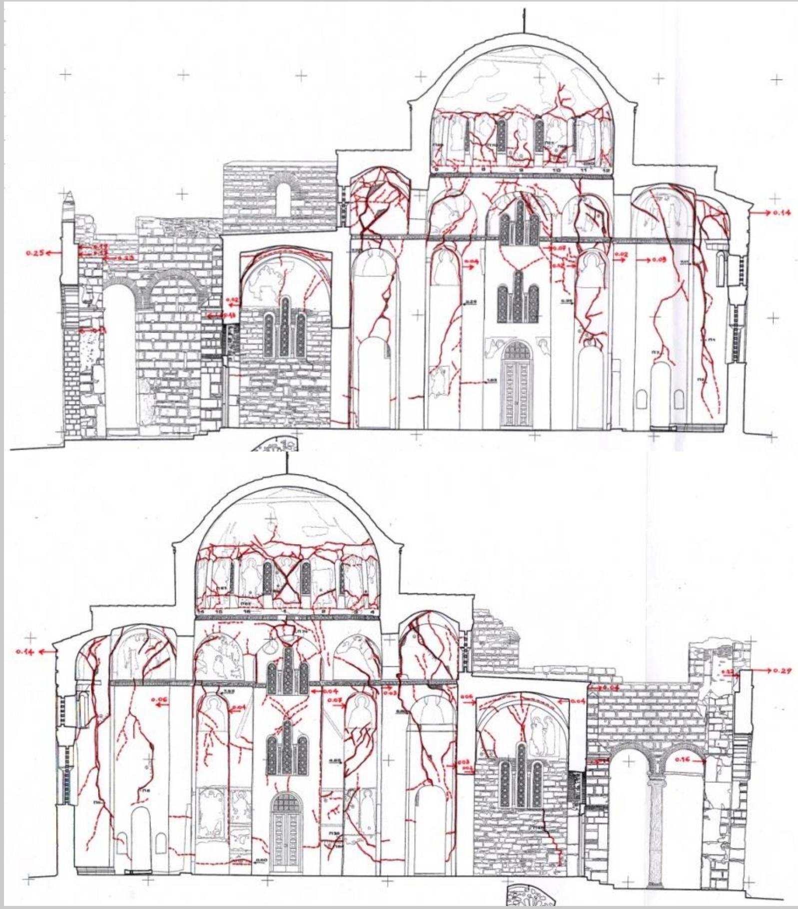
(d) Photogrammetry: Survey of the monument-Fac. of Survey Eng./NTUA

(e) Borings-geotechnical data: Faculty of Civil Engineering/ NTUA

(f) Chemical analysis of materials-Aristotle Univ. of Thessaloniki

(g) Structural behaviour of the monument-Lab. of RC/NTUA

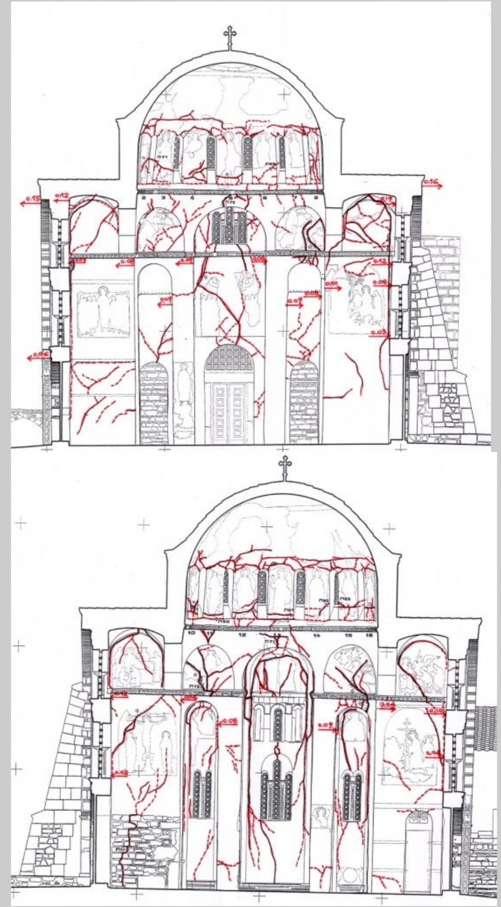
DOCUMENTATION AND INTERPRETATION OF PATHOLOGY



LONGITUDINAL SECTIONS

MORE SEVERE DAMAGES TOWARDS THE WEST

EAST: PIERS OF THE ALTAR, EAST STRONG WALL
WEST: FREE STANDING ISOLATED PIERS
NARTHEX: ONLY PERIMETER WALLS



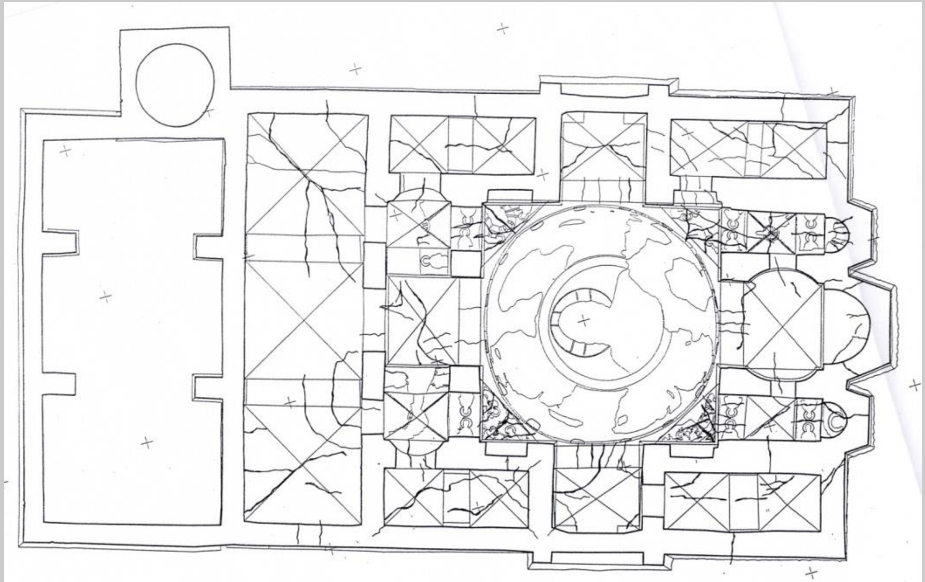
TRANSVERSE SECTIONS

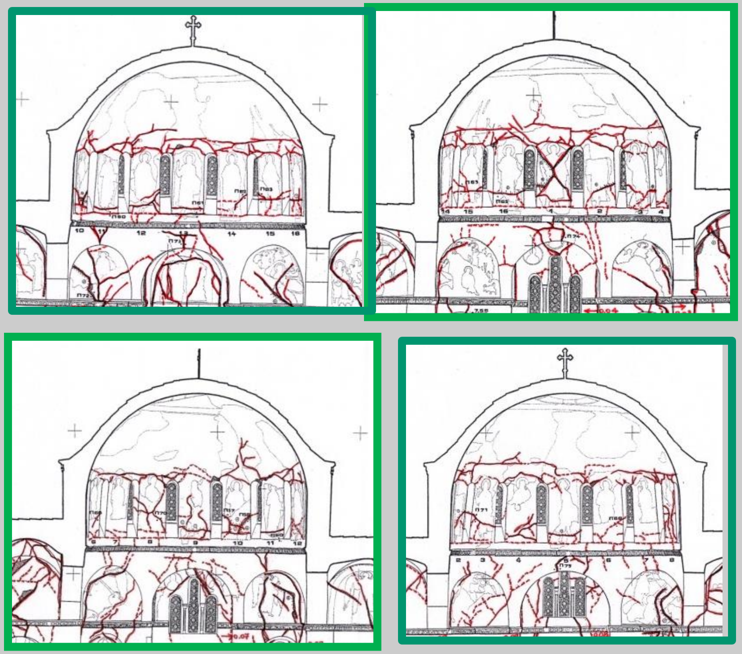
MORE SEVERE DAMAGES TOWARDS THE TOP (WHERE MOSAICS ARE LOCATED)

SIGNIFICANT OUT-OF-PLANE DISPLACEMENTS OF THE WALLS, ESPECIALLY ALONG THE N-S DIRECTION (SMALLER STIFFNESS)

DOCUMENTATION AND INTERPRETATION OF PATHOLOGY

PATHOLOGY OF DOMES AND VAULTS





Sum of crack openings in east-west direction

39,90mm +5,70

18,90mm +2,90

12,50mm +1,50

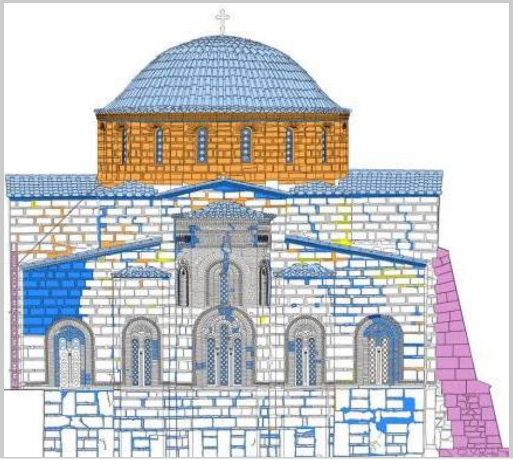
Documented by the frozen out-of-plane displacement of south wall, as well as by analytical work.

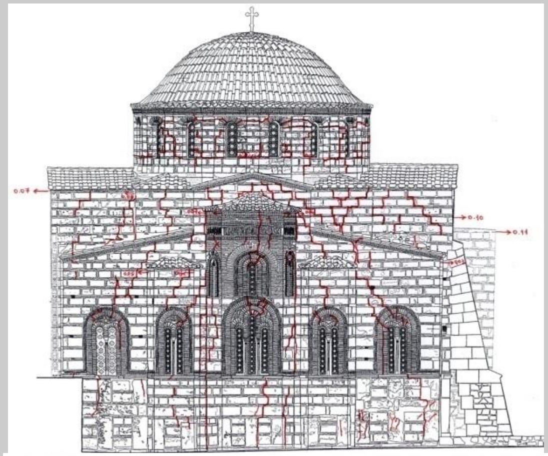
Therefore, there is a tendency of the building "to open" in the north-south direction

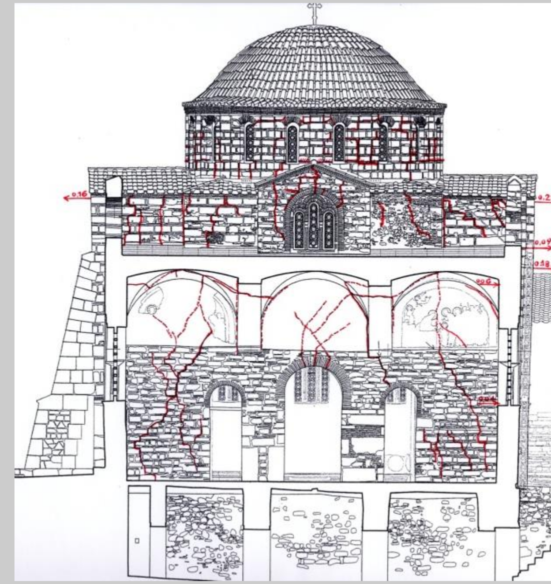
DOCUMENTATION AND INTERPRETATION OF PATHOLOGY

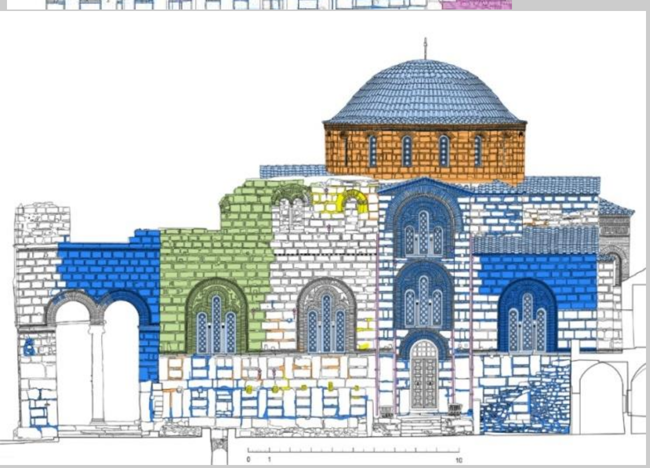
HISTORICAL PATHOLOGY

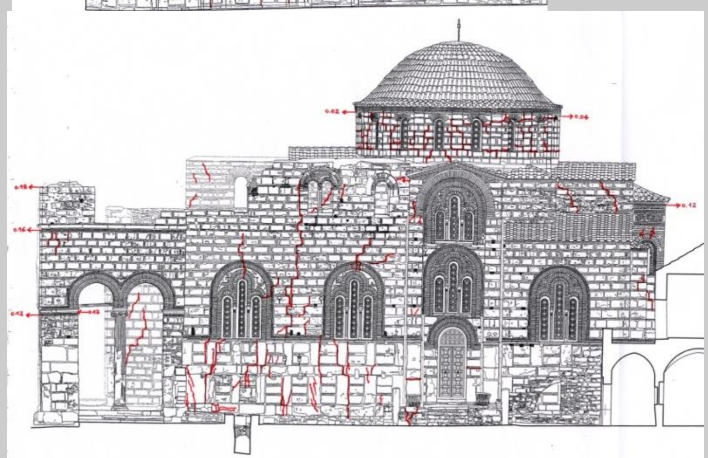
RECENT PATHOLOGY











FURTHER OUT-OF-PLANE DEFORMATIONS TO THE RECONSTRUCTED REGIONS

SIMILAR DAMAGES

MAJOR CONCLUSION

Repair measures taken up to 1999 were unable to protect the monument from severe damages.

Presumably, a future earthquake will cause losses not only to the building but also to the precious mosaics.

STRENGTHENING IS NEEDED

To reduce the vulnerability of the monument against seismic actions and, thus, to reduce the damages due to future seismic events.

THUS, A SPECIFIC STUDY IS NEEDED FOR THE SELECTION OF THE OPTIMAL INTERVENTIONS (ASSESSMENT OF THE EFFICIENCY OF VARIOUS TECHNIQUES, USING-AS MUCH AS POSSIBLE-RELIABLE DATA AND RELIABLE MODELS AND ANALYTICAL METHODS).

ESTIMATION OF CURRENT RESISTANCES

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

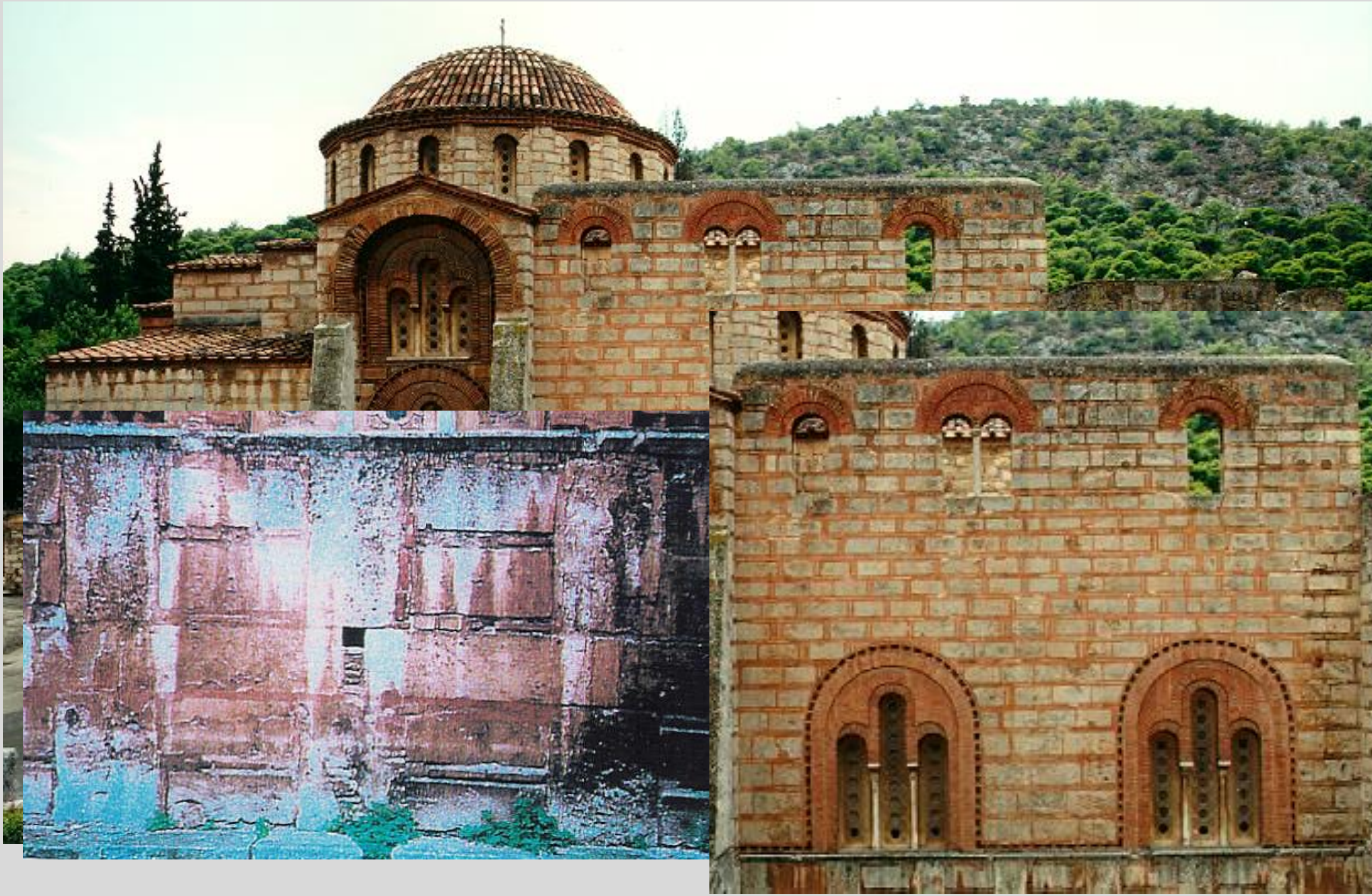
Estimation of mechanical properties of masonry, using empirical formulae from the literature. It has led to very low values.

If the mechanical properties of masonry are underestimated, there is a risk of proposing extensive interventions that may not ne needed!

In-laboratory assessment of mechanical properties of masonry before and after grouting.

Preparation of masonry for the application of grout), waiting for the experimental data…

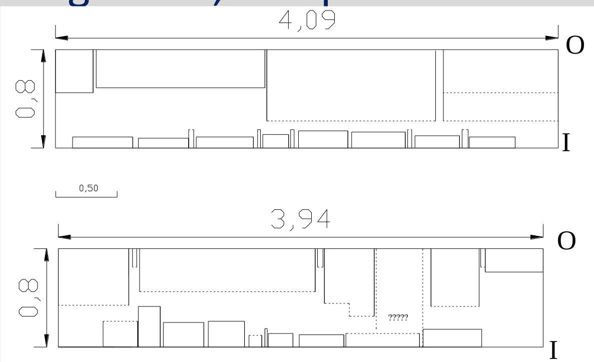
IDENTIFICATION OF CONSTRUCTION TYPE OF MASONRY

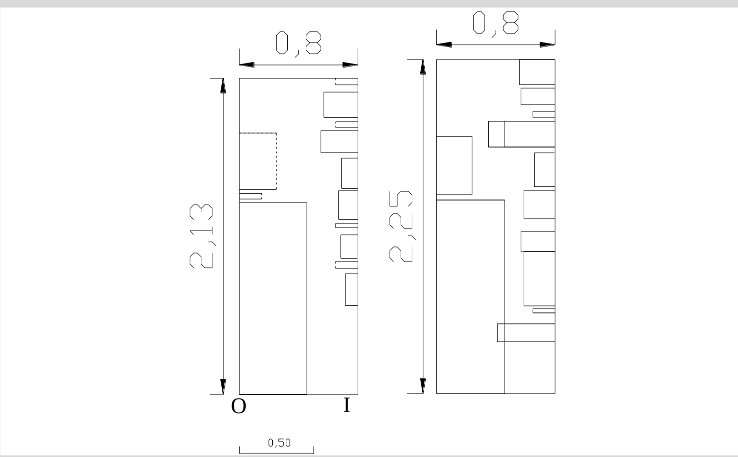


IDENTIFICATION OF CONSTRUCTION TYPE OF MASONRY

Investigation through radar and boroscopy (for verification).

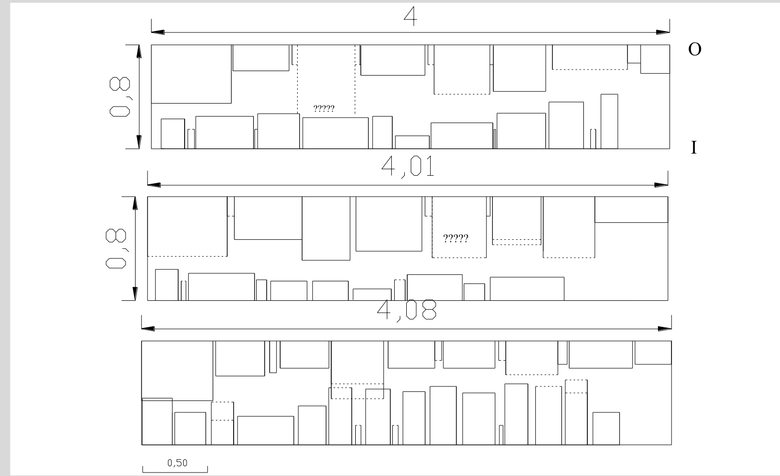
In general, compatible results.

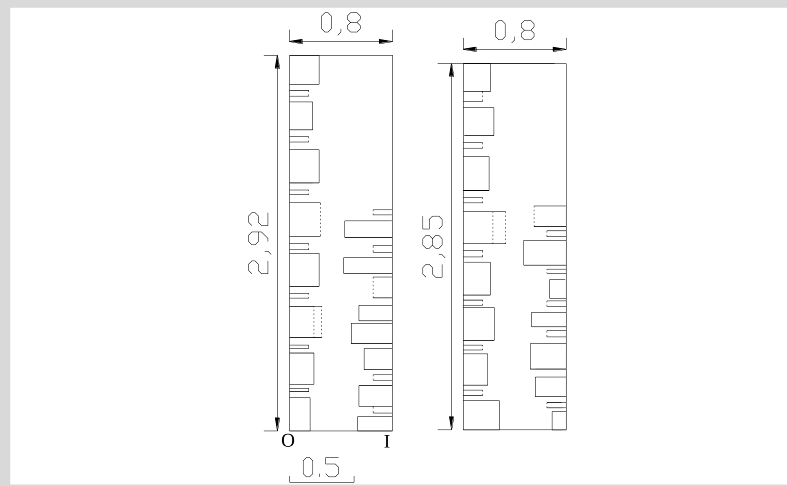




Lower zone (hor./vert.)

0,24m thick intermediate leaf



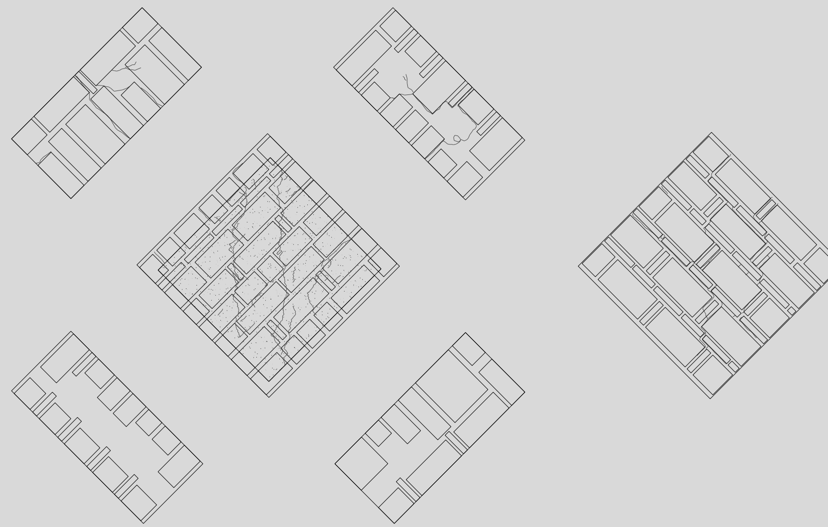


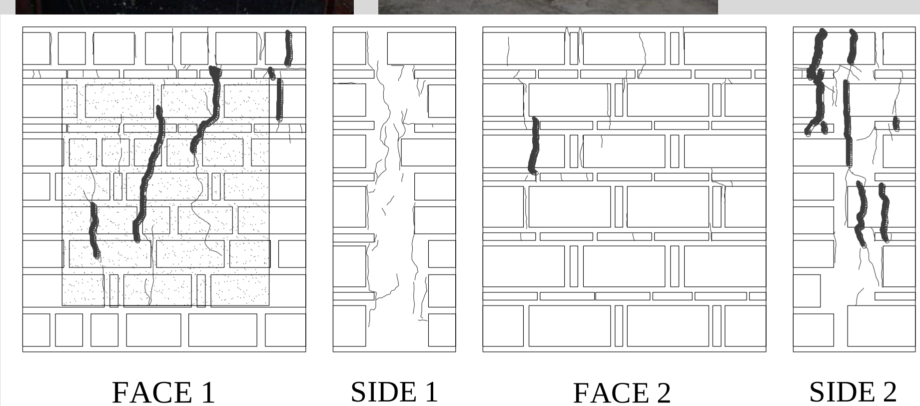
Upper zone (hor./vert.)

0,32m thick intermediate leaf

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

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





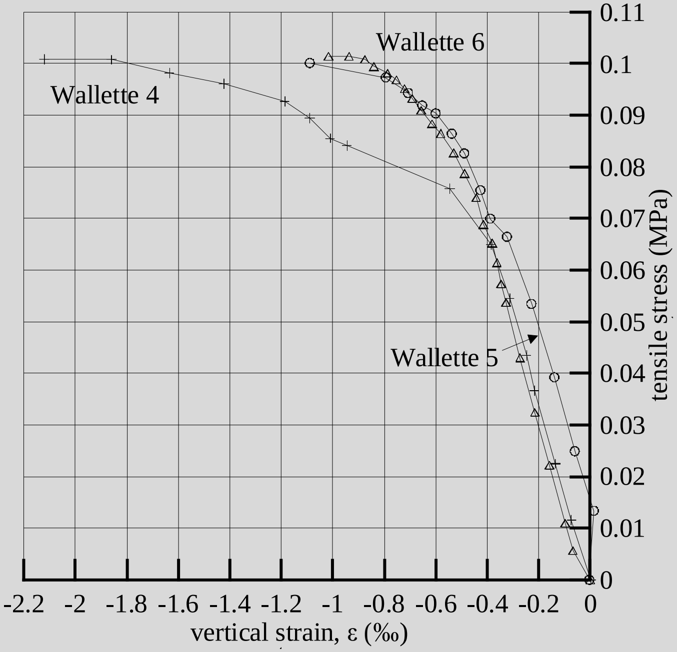
IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

Wallettes in compression

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

Wallettes in diagonal compression



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.

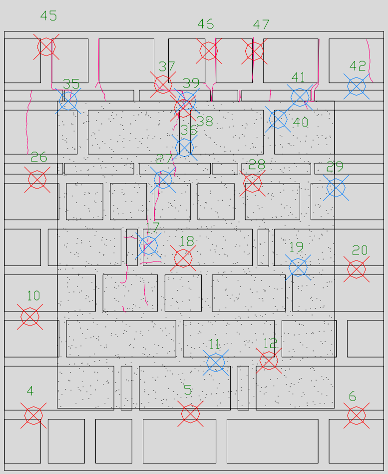
IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

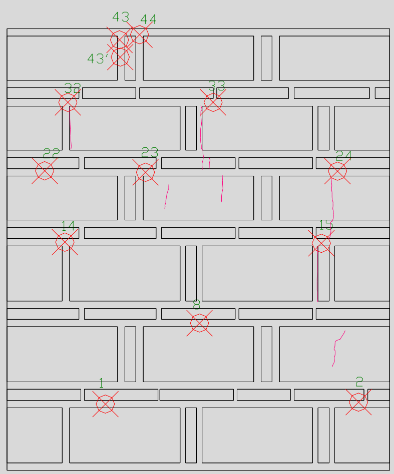
Drilling of holes and installation of plastic tubes

Drilling holes

Sealing cracks

Installing tubes





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

Holes deep enough to reach filling material

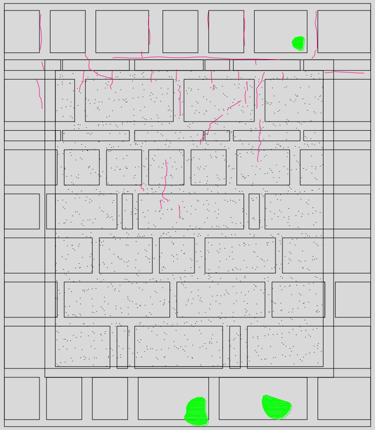
Transparent tubes (1.0 to 10.0mm)

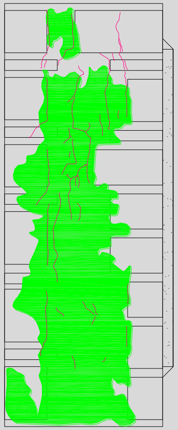
Tubes are numbered and reported on drawings

IN-LABORATORY ASSESSMENT OF MECHANICAL PROPERTIES OF MASONRY

Application at low pressure (0.5-1.0 bar). Average percentage of voids:~37%

Humidity on wall surface

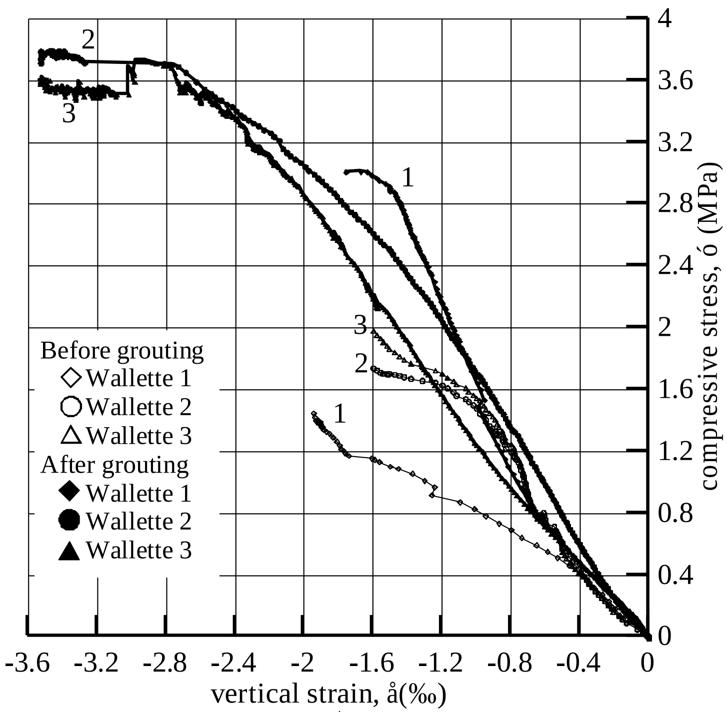




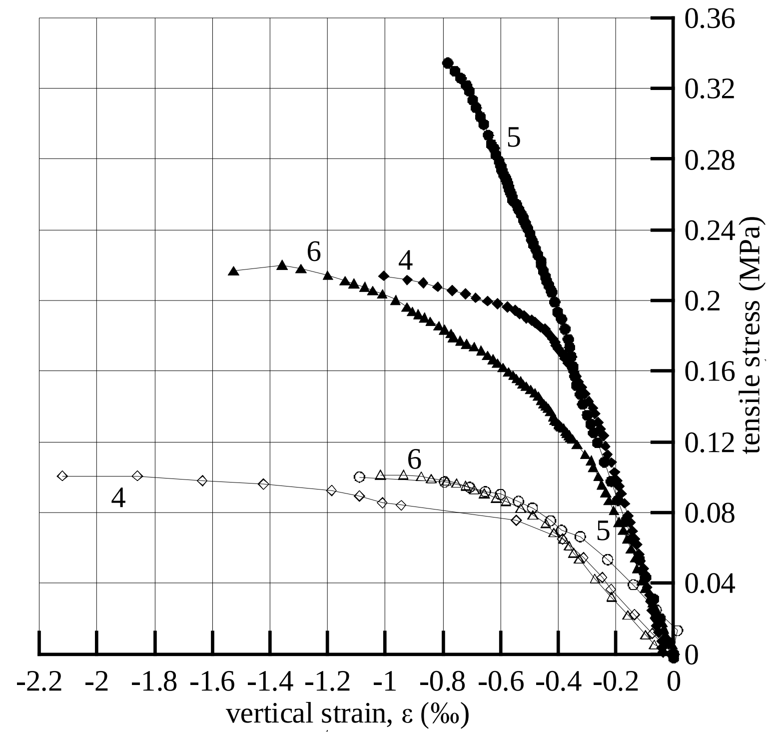
Mixer and mechanical device for mixing the grout during injection

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



Compression



Diagonal compression

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.

BEHAVIOUR OF A CROSS VAULT

PIERS

- **Grouting** of diagonal cracks [natural hydraulic lime based grout using **S&B pozzolan** (perlite)].
- Strengthened for out-of-plane bending, using **post-tensioned CFRP plates** placed vertically on both faces of the piers (CarboDur 624, **SIKA**), (0.20MPa per pier).

ARCH/VAULT

- **Grouting of cracks** of the arch and the vault .
- **Horizontal timber elements** (struts) and **steel elements** (ties) at the base of the arches.

BEHAVIOUR OF A CROSS VAULT

Vertical prestressing of piers

Irpinia, Italy, 1980 Earthquake

No. of test	Excitation	Direction of excitation	Amplification of original record
1	White-noise	Y	–
2	White-noise	X	–
3	White-noise	Z	–
4	Irpinia earthquake	X	30%
5	Irpinia earthquake	X	50%
6	Irpinia earthquake	X	75%
7	Irpinia earthquake	X	100%
8	Irpinia earthquake	X	125%
9	Irpinia earthquake	X	150%
10	Irpinia earthquake	X	175%
11	Irpinia earthquake	X	200%
12	Irpinia earthquake	X	250%
13	Irpinia earthquake	X	300%
14	Irpinia earthquake	X	350%
15	Irpinia earthquake	X	400%
16	Irpinia earthquake	[illegible]	[illegible]
17	Irpinia earthquake	[illegible]	[illegible]
18	Irpinia earthquake	[illegible]	[illegible]
19	Irpinia earthquake	X-Y	100%
20	**Irpinia earthquake**	**X-Y**	**150%**

No. of test	Excitation	Direction of excitation	Amplification of original record
1	Sine sweep	X	–
2	Sine sweep	Y	–
	Application of vertical load		
3	Sine sweep	X	–
4	Sine sweep	Y	–
5	Irpinia earthquake	X-Y	50%
6	Irpinia earthquake	X-Y	100%
7	Irpinia earthquake	X-Y	150%
8	Irpinia earthquake	X-Y	200%
9	Irpinia earthquake	X-Y	250%
10	Irpinia earthquake	X-Y	300%
11	Irpinia earthquake	X-Y	350%
12	Irpinia earthquake	X-Y	400%
13	**Irpinia earthquake**	**X-Y**	**450%**
14	Sine sweep	X	–
15	Sine sweep	Y	–

DESIGN OF INTERVENTIONS AND APPLICATION IN TWO PHASES

AIM

THE MINIMUM REQUIRED STRENGTHENING INTERVENTIONS THAT WILL BE JUDGED TO BE OPTIMAL, TAKING INTO ACCOUNT THE VALUES OF THE MONUMENT

THE DECISION:

1ST PHASE OF INTERVENTIONS
Strengthening of masonry (re-jointing, grouting, re-construction, etc.)

Completed, 2007

+

DOCUMENTATION-INVESTIGATIONS FOR THE REDUCTION OF UNCERTAINTIES

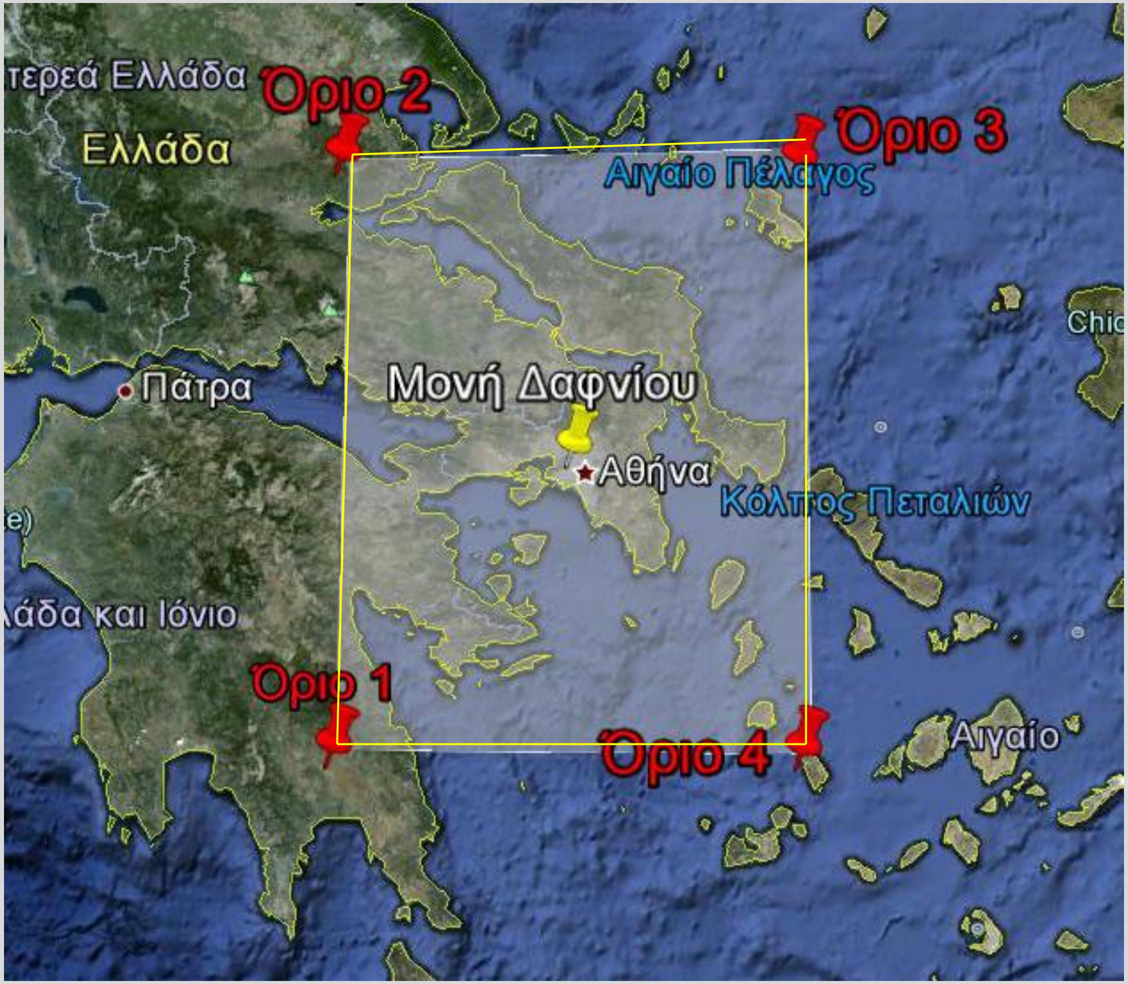
- **Geometry/materials of hidden areas**
- **Assessment of masonry resistances before and after grouting**
- **Seismic risk assessment**
- **Dynamic identification through monitoring**

2012: THE DESIGN OF MEASURES OF THE 2ND PHASE WAS COMPLETED

2ND PHASE OF INTERVENTIONS
Strengthening measures (confinement of piers, struts/ties, diaphragms, etc.)

SEISMIC RISK ASSESSMENT

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).

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

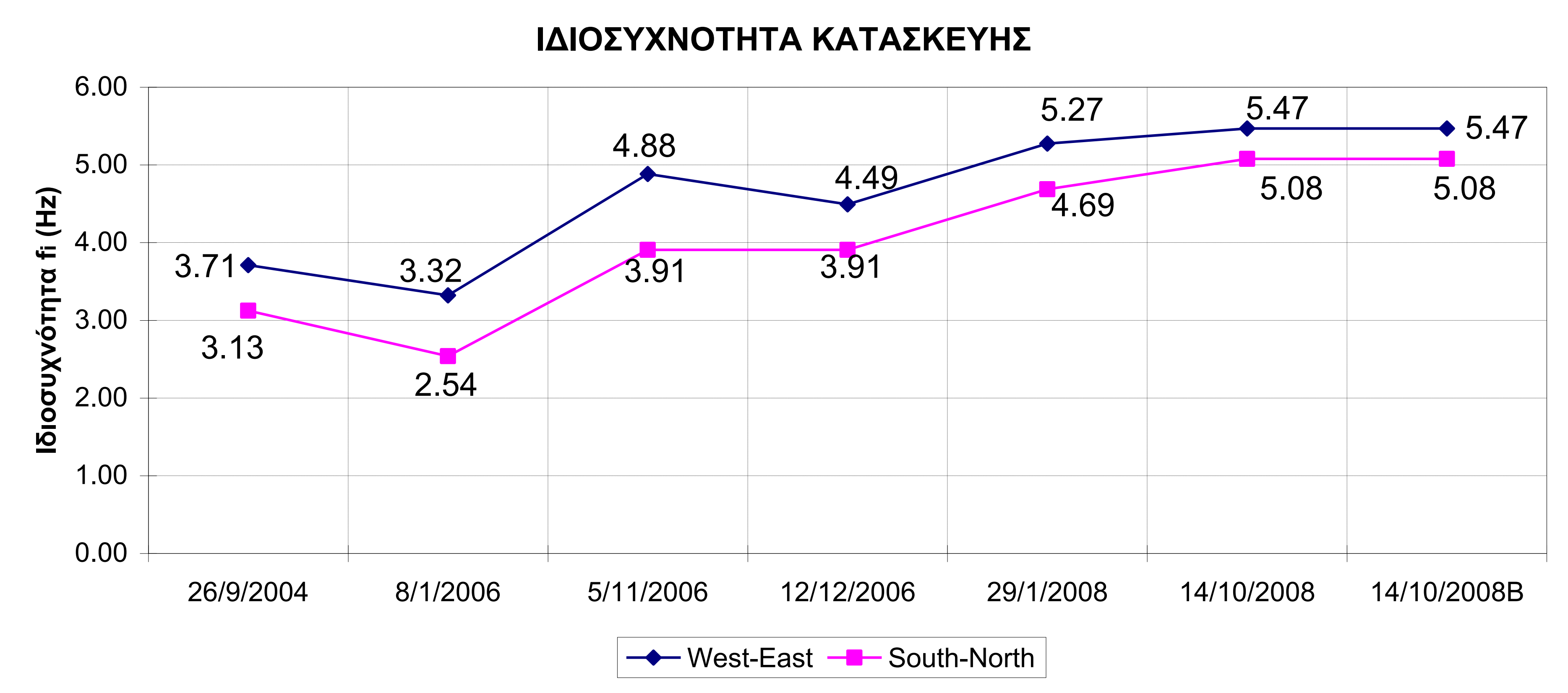
- THE EQUIPMENT
- **Accelerometres**: Measuring the acceleration due to an earthquake at three levels (interior and exterior of the monument), as well as on the ground.
- **Displacement-metres**: Measuring displacements in the interior of the monument (at the base of the system of domes and vaults) .

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

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.

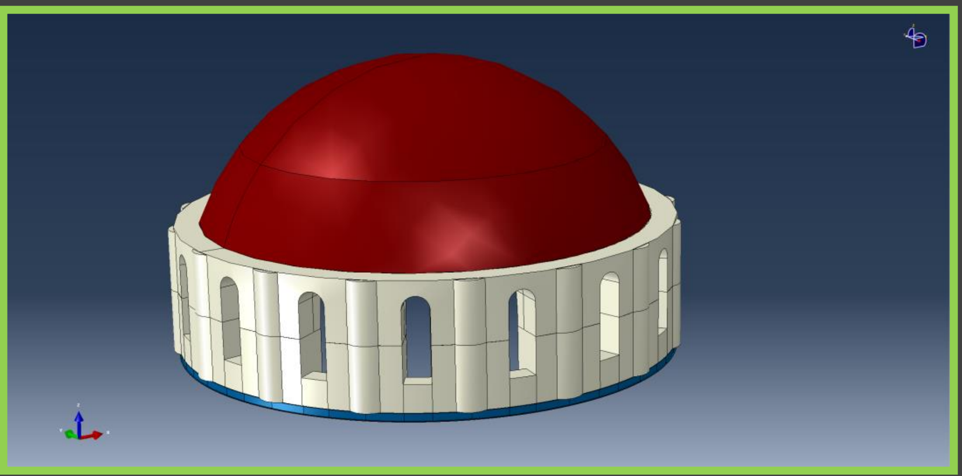
b) Design of interventions, after in-situ check of their applicability, taking into account the actual geometry of various parts of the monument and, of course, the locations of mosaics that must be protected.

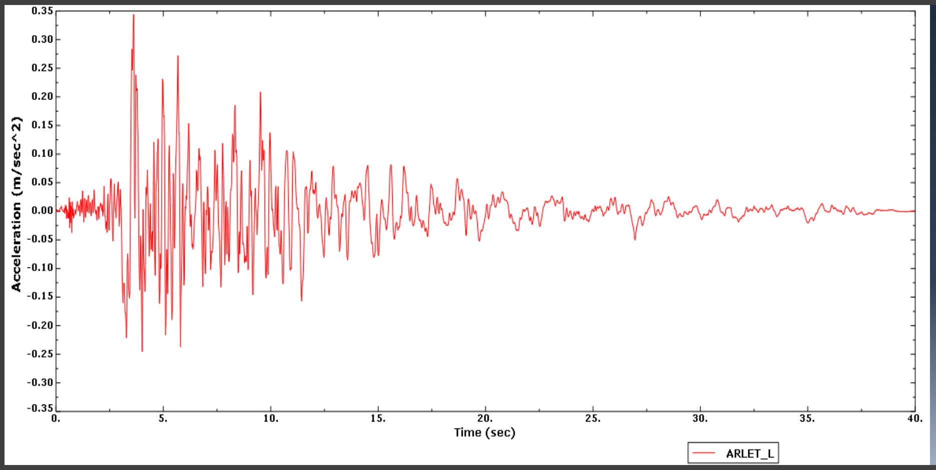
c) All 3D drawings that are necessary for the proposed interventions to be identified, as well as adequate plans and sections, so that the possibility of applying hidden and visible interventions be fully documented. The effects of the interventions on the appearance of the monument should also be fully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

NEW MODELS

THE CUPOLA

THE ENTIRE MONUMENT





Equivalent static analysis

Equivalent static analysis

and
Time-history analyses

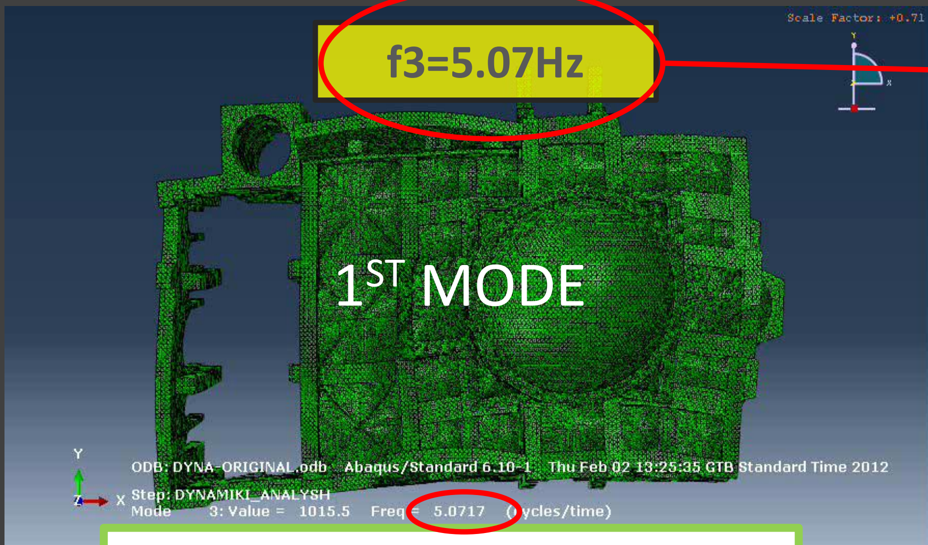
CALIBRATION OF MODELS

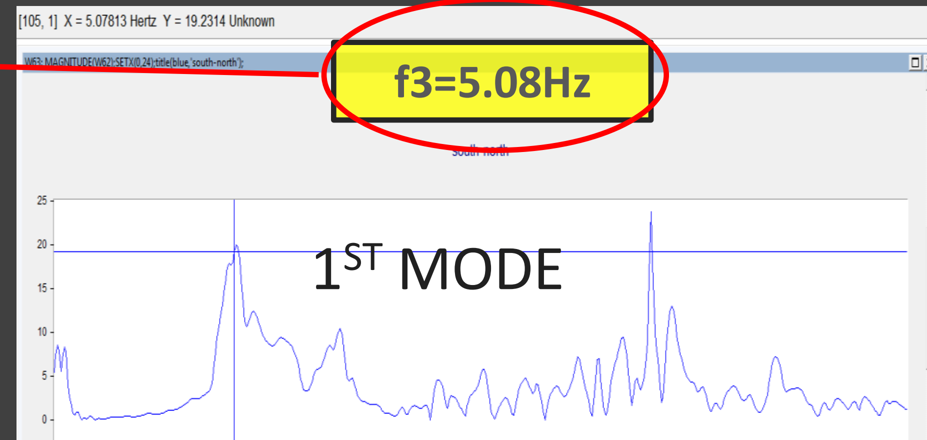
MONITORING SYSTEM

THE DATA WERE USED FOR THE CALIBRATION OF THE MODELS

CALIBRATION OF MODELS

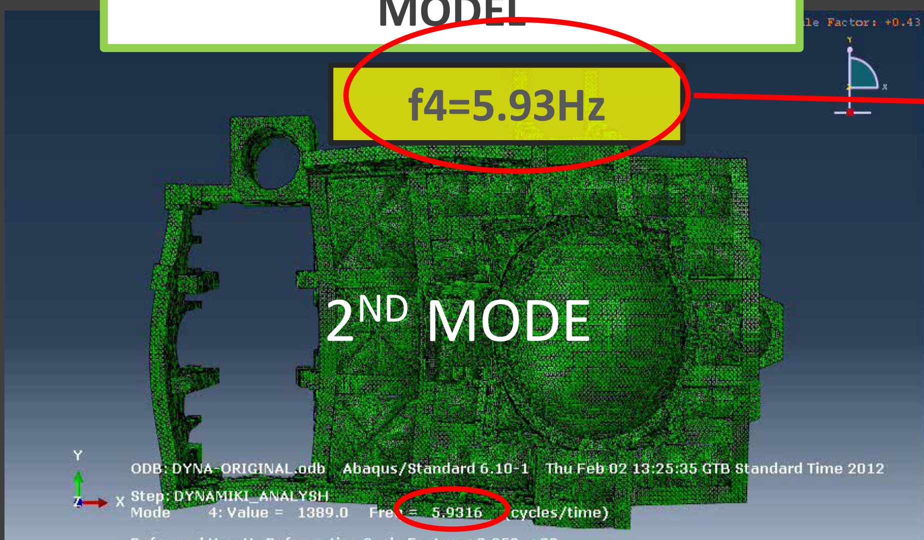
EIGEN-FREQUENCIES

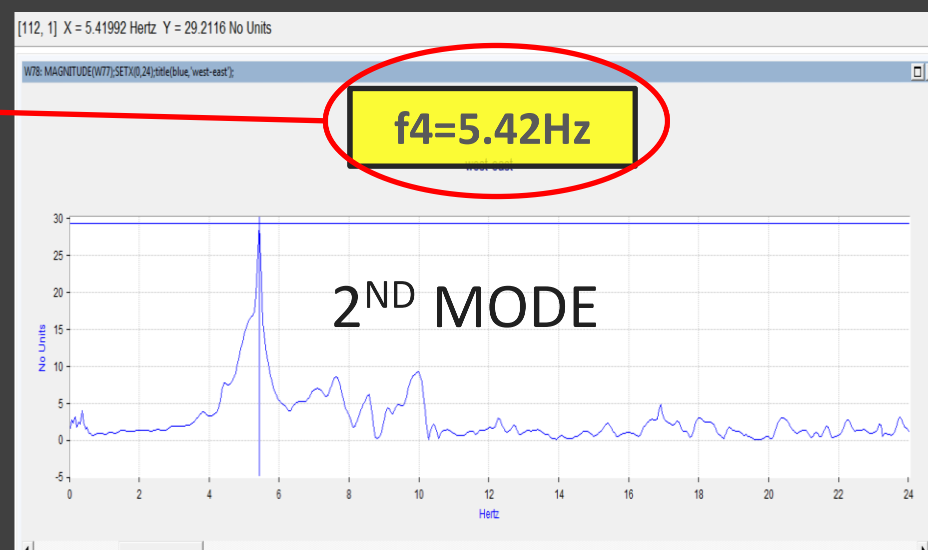




RECORDING OF EARTHQUAKES

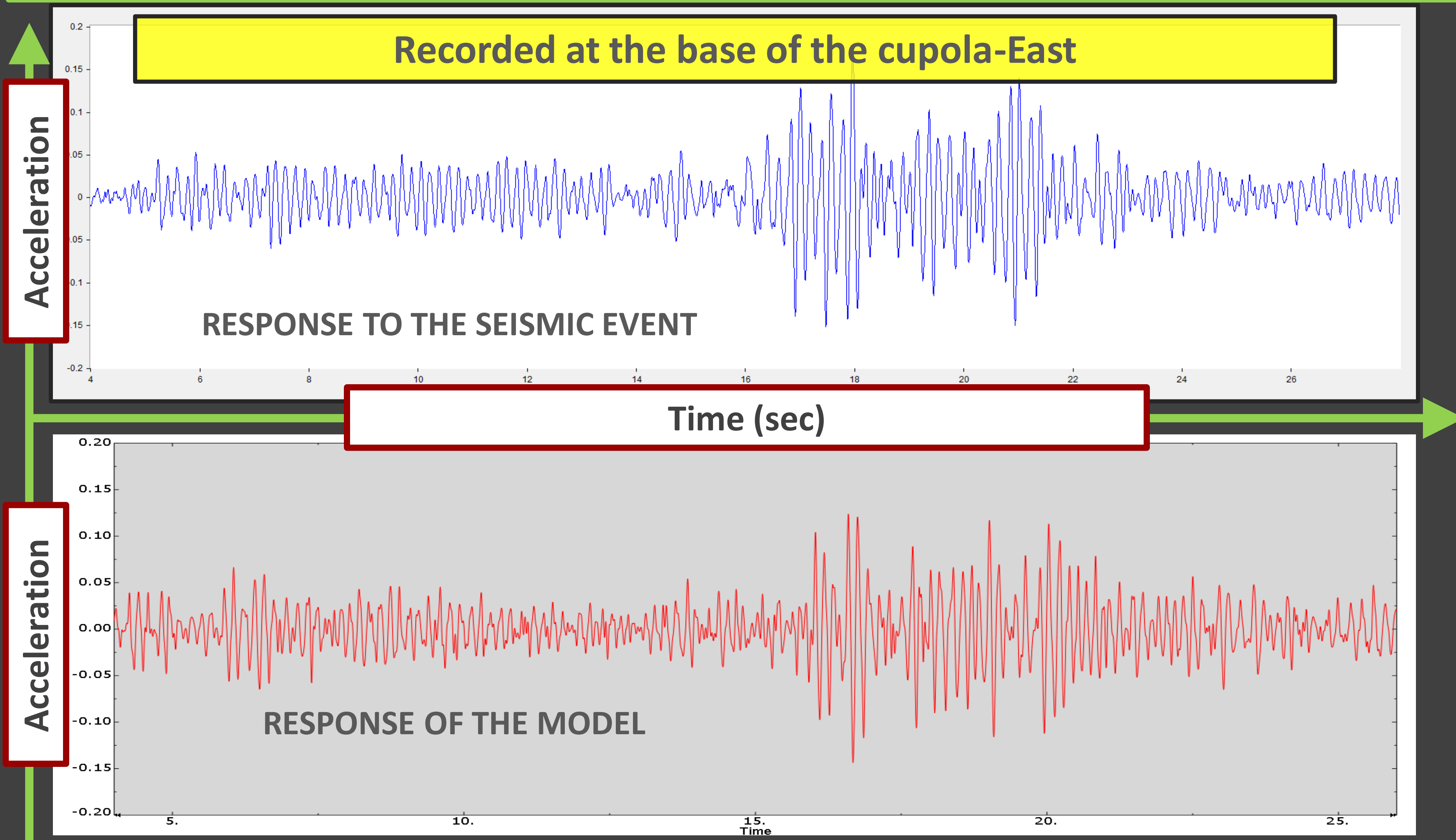
MODEL



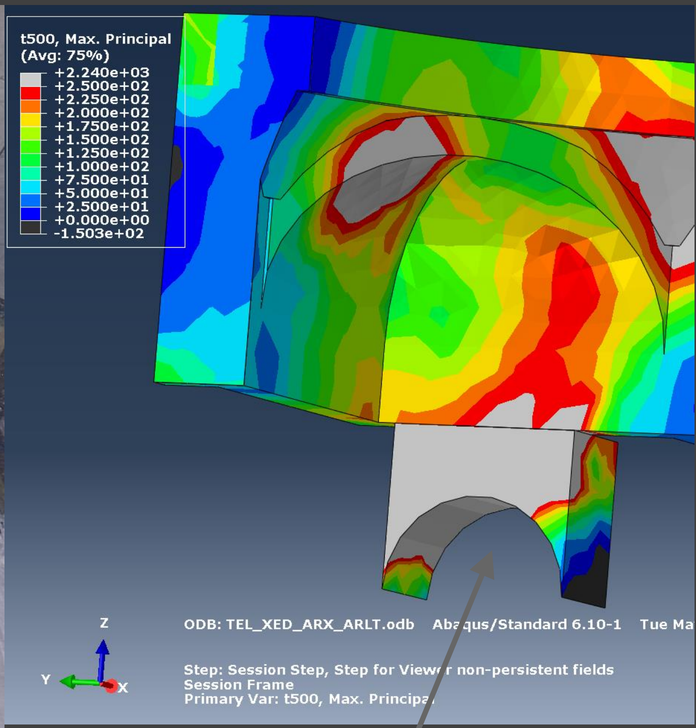


CALIBRATION OF MODELS

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

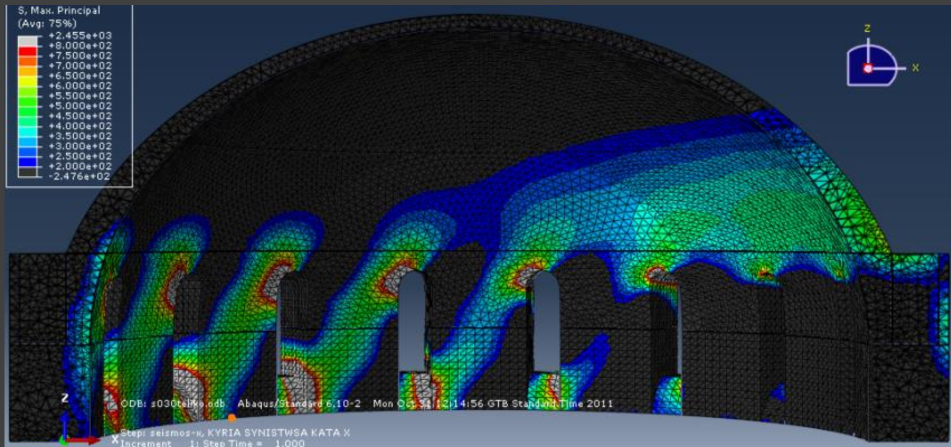


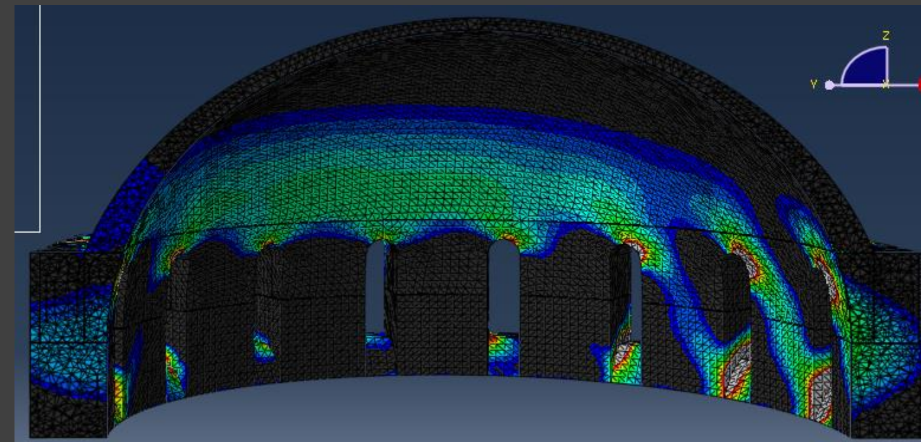
REPRODUCTION OF OBSERVED DAMAGES-PENDATIVES-ARCHES



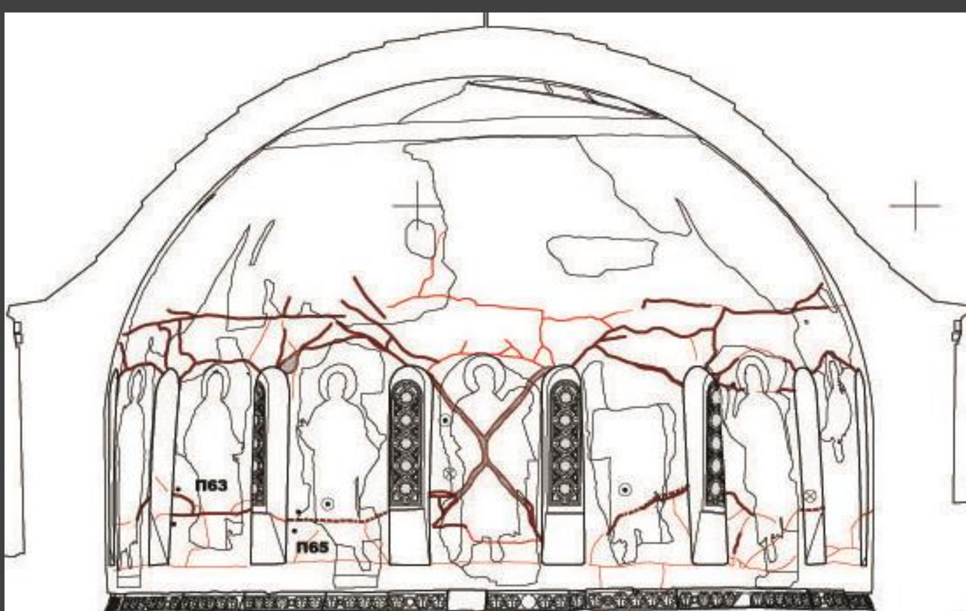
MAXIMUM TENSILE STRESSES
FOR THE BEARING SYSTEM
BEFORE INTERVENTIONS

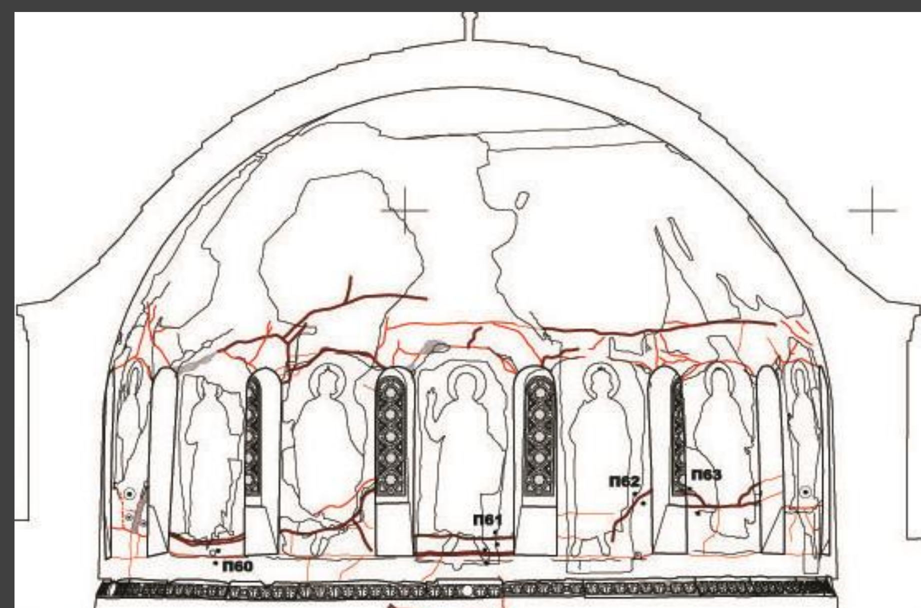
REPRODUCTION OF OBSERVED DAMAGES-CUPOLA



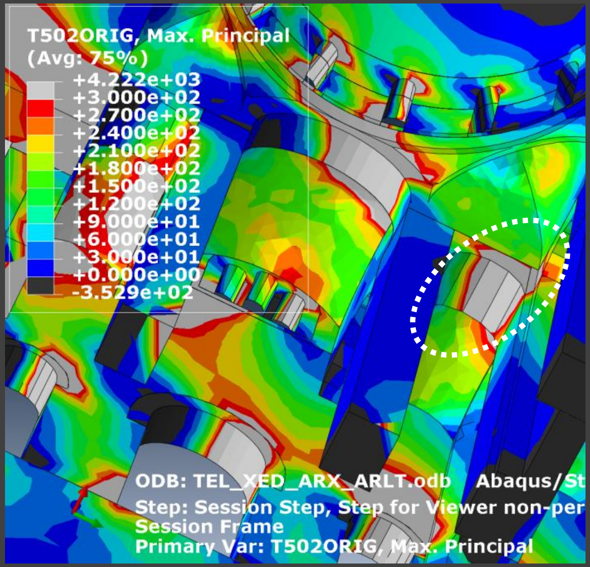


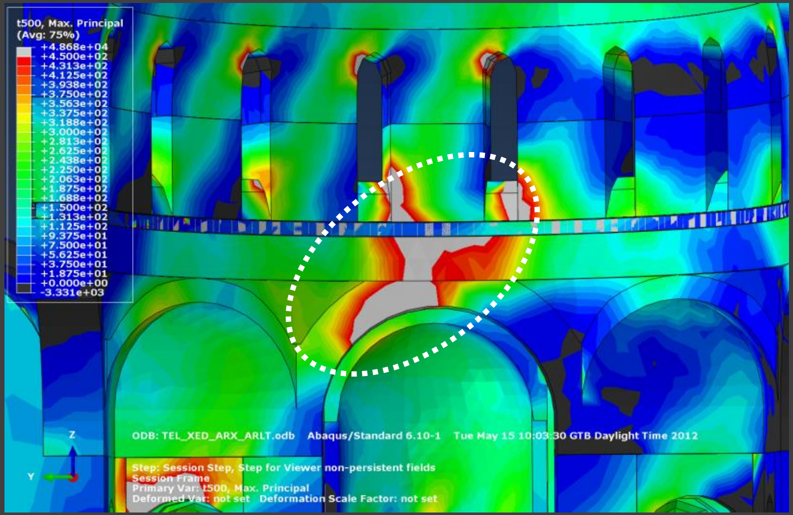
EAST WEST NORTH SOUTH





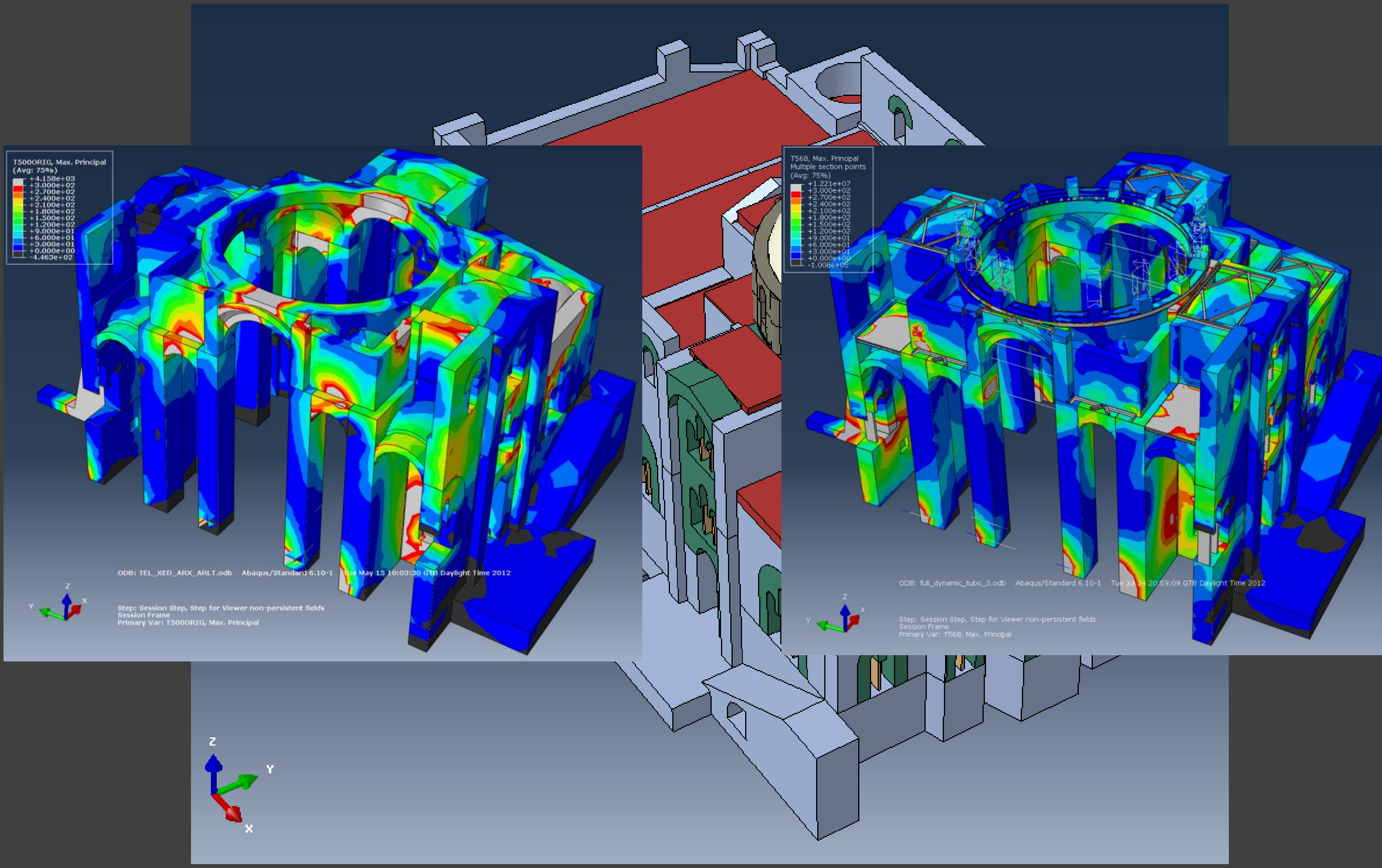
REPRODUCTION OF OBSERVED DAMAGES



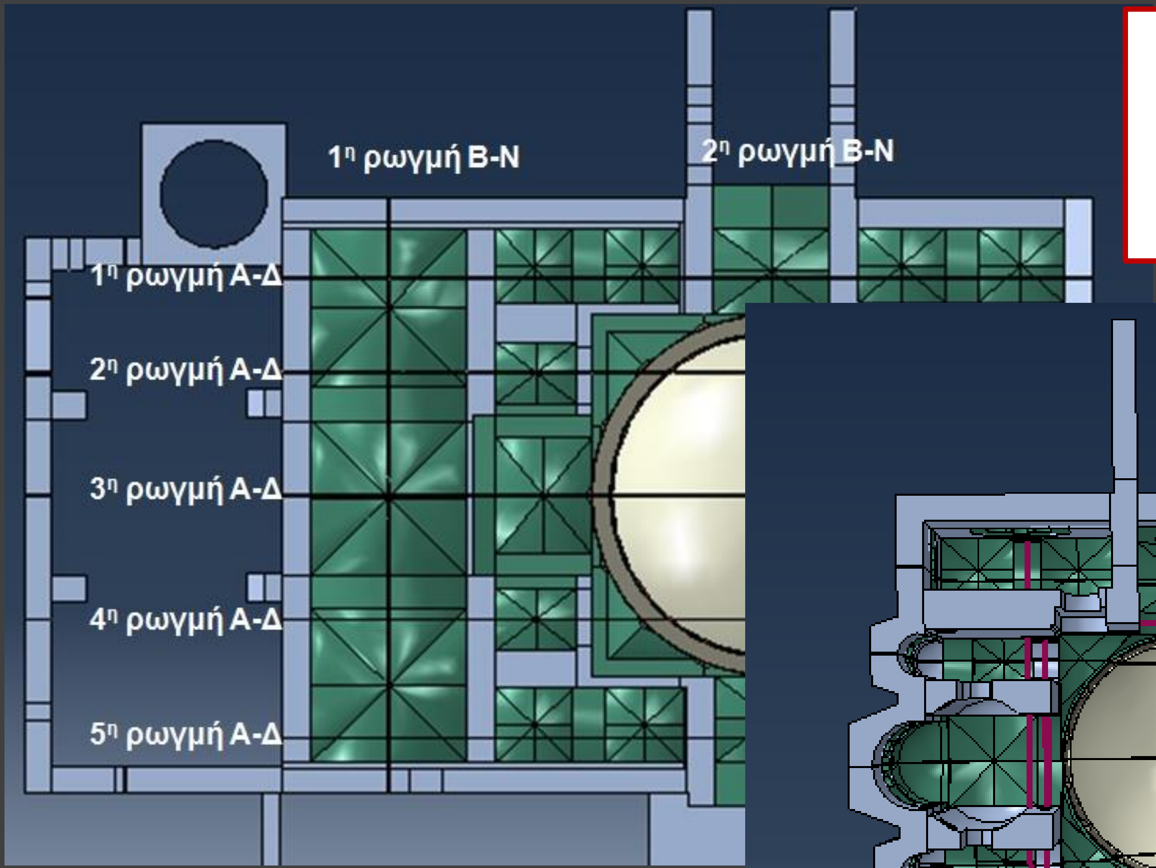


ASSESSMENT OF EFFICIENCY OF ALL INTERVENTION MEASURES ON THE ENTIRE BUILDING

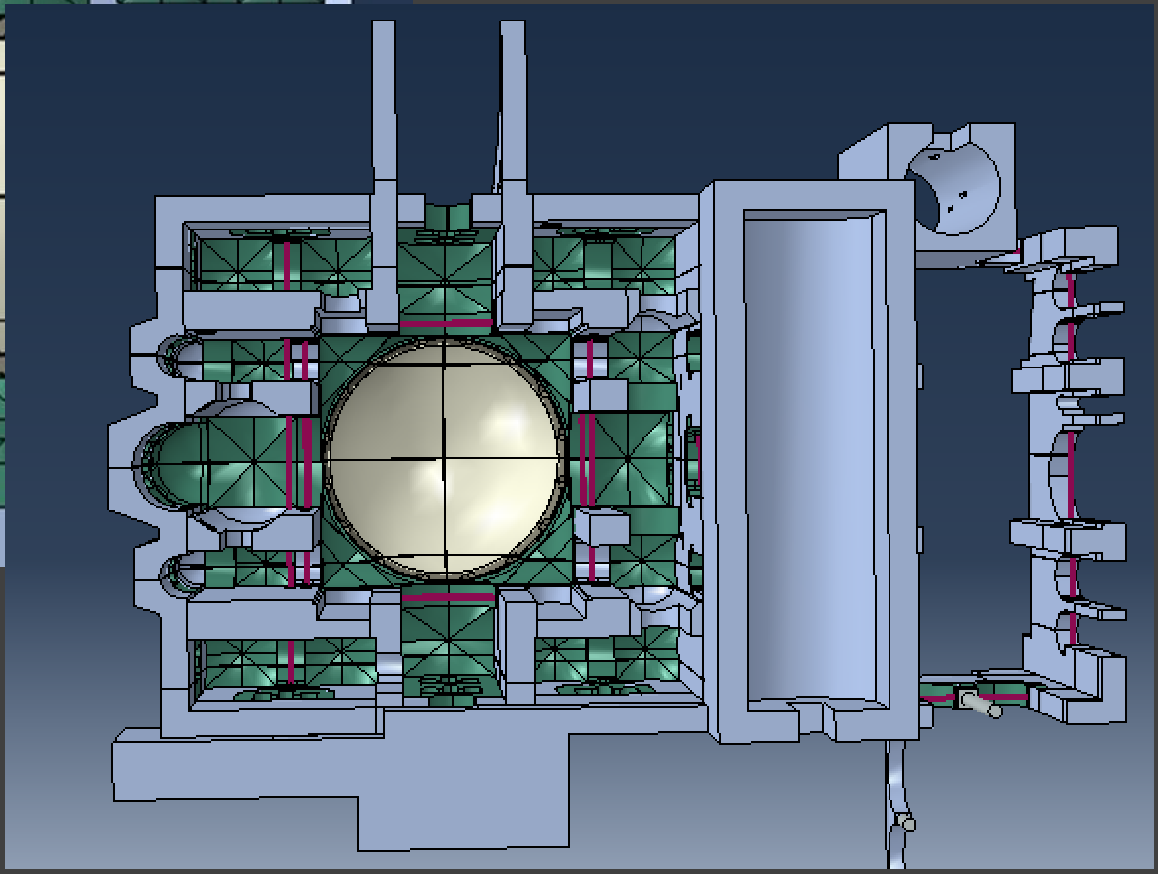
Example 1. Diaphragms at the extrados of domes and vaults



ALTERNATIVE INTERVENTION MEASURES-analysis of the entire building



Example 2. Struts and ties/Cracked bearing system



Dimensioning of ties

INTERVENTIONS

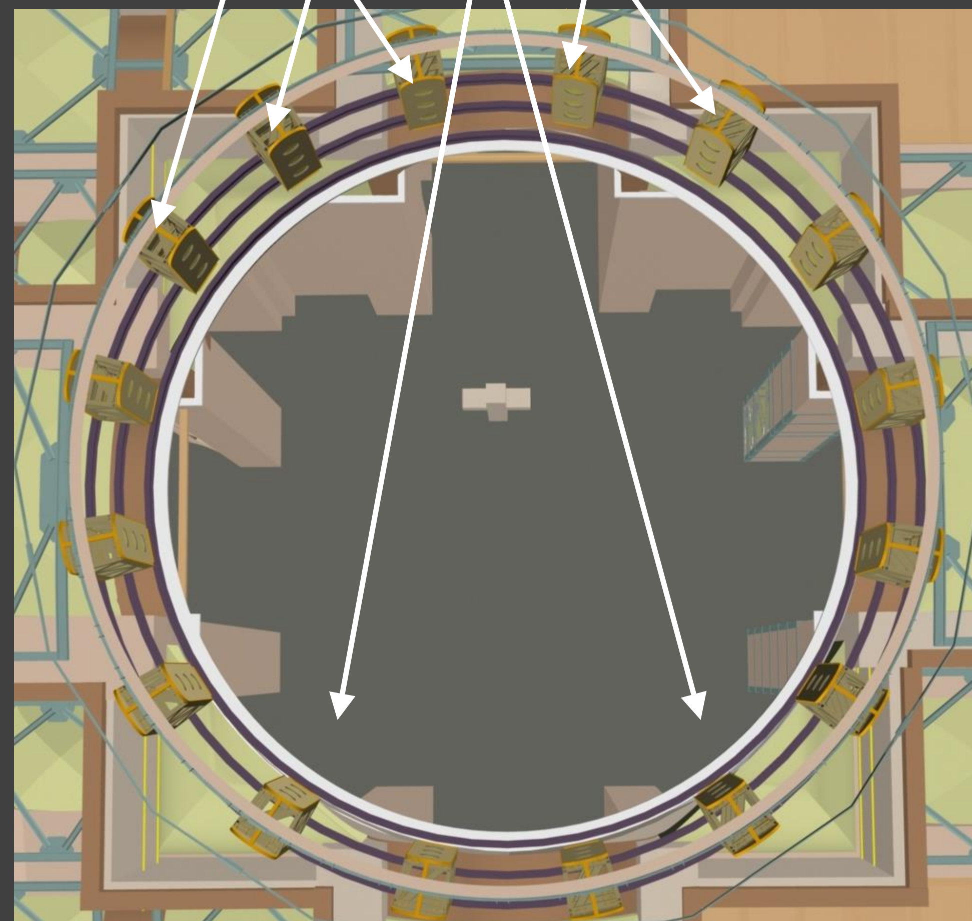
Replacement of existing steel ring

New (stainless) steel ring

New (non visible) steel ring at the extrados of the cupola

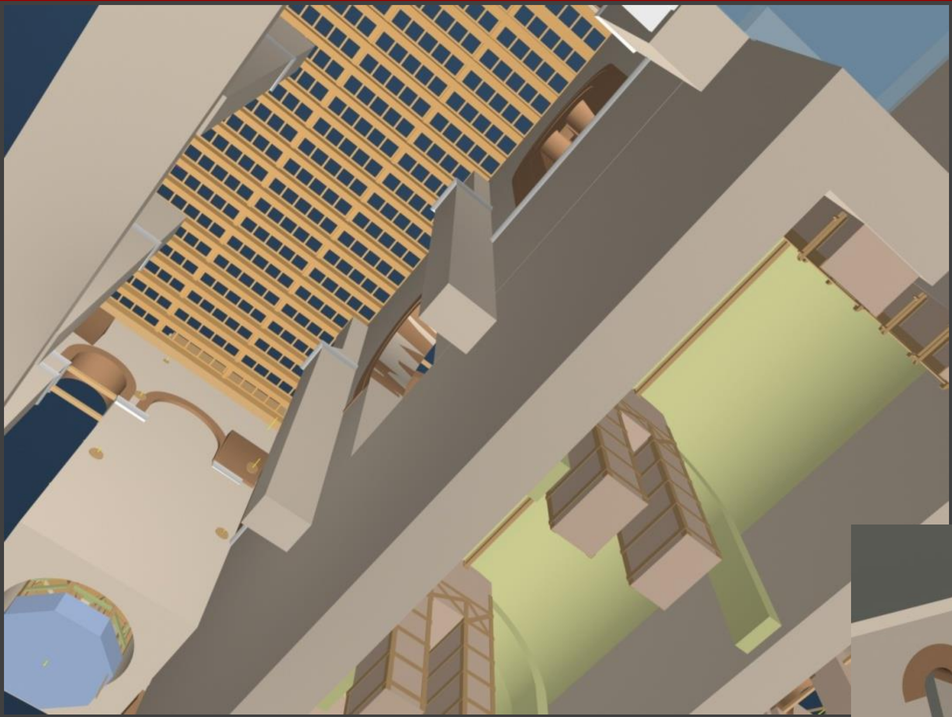
INTERVENTIONS

New steel stiffening frames in the openings of the drum



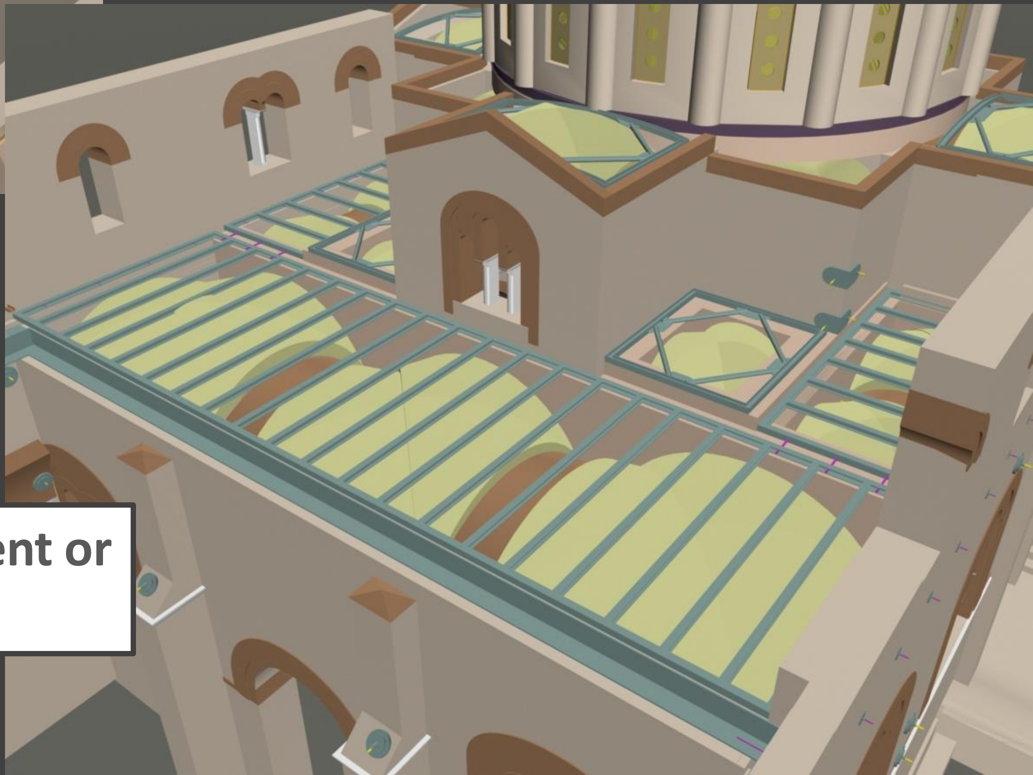
Diaphragms at the extrados of domes and vaults & diaphragm at the exo-narthex

INTERVENTIONS



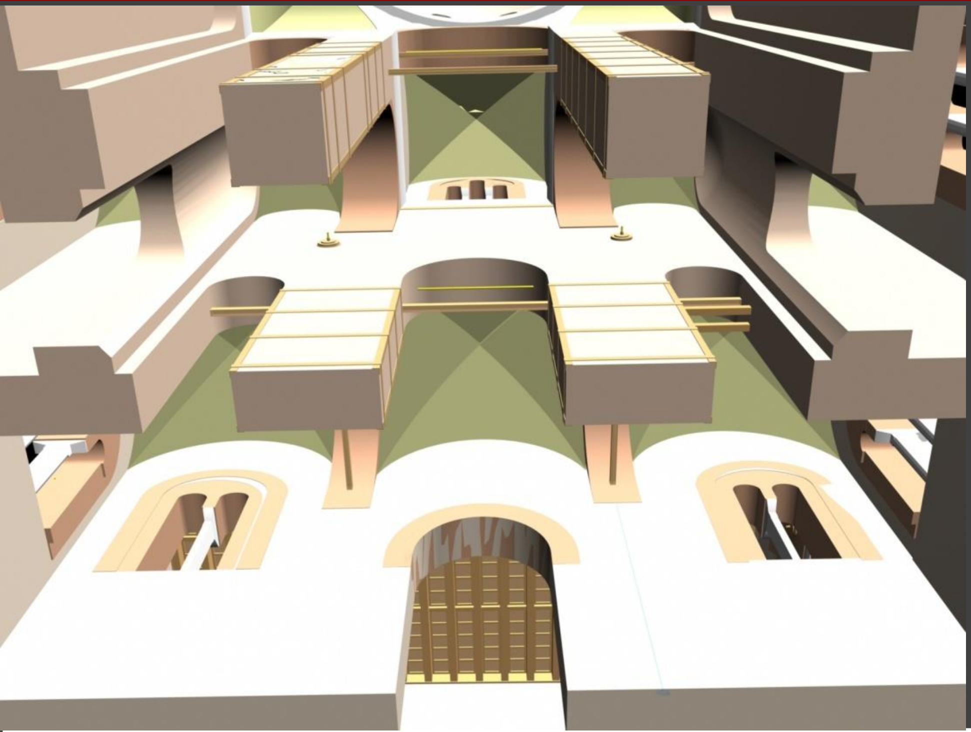
Timber floor and pavement

Diaphragm at the western part

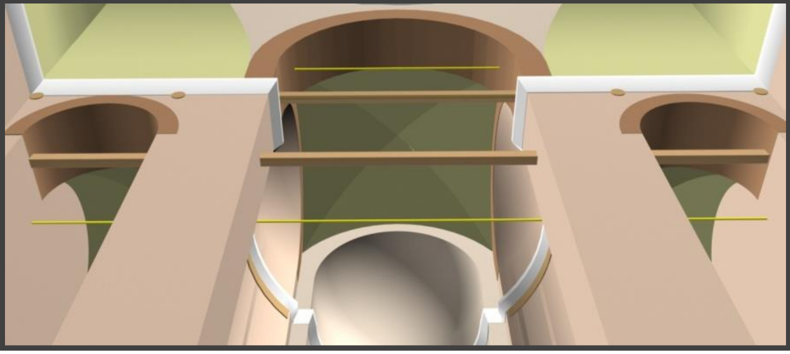


Steel diaphragms with timber pavement or without pavement

INTERVENTIONS



Ties/Struts-Narthex



Ties/Struts-main church

Ties/West wall

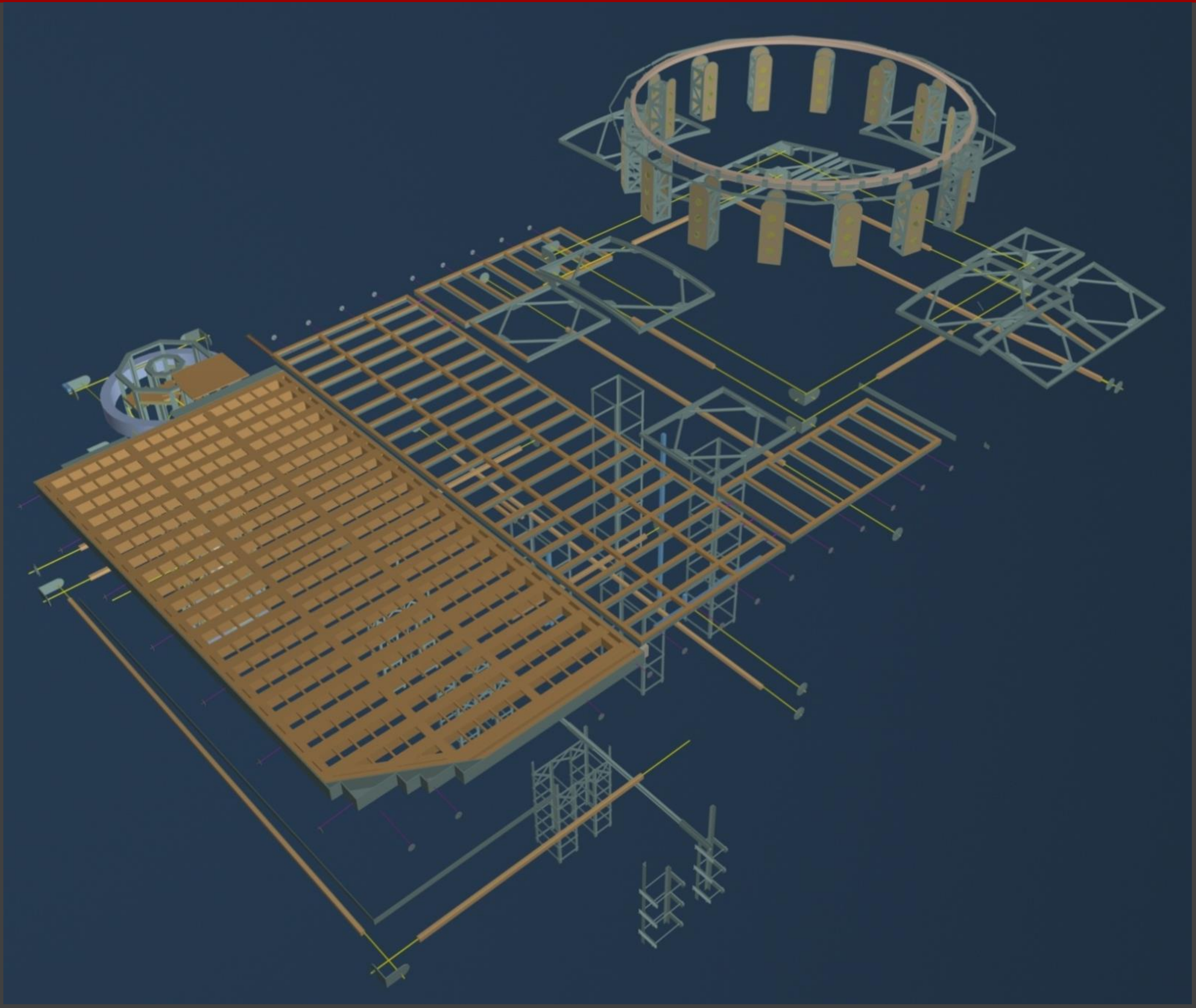
Steel jackets of piers

View of the monument after intervention

INTERVENTIONS

View of the monument after intervention

INTERVENTIONS



MOST OF THEM-INVISIBLE

EFFICIENCY OF INTERVENTION MEASURES

Significant improvement of the seismic behaviour of the monument is achieved. However, damages are to be expected in case of a strong earthquake!

The entire work for the documentation and for the design of immediate measures was performed by a group supervised by Dr Androniki Miltiadou (Str.Engineer) and N.Delinicolas (Architect).
Group for the design of the final intervention measures: Dr A.Miltiadou, N.Delinicolas, E.Vintzileou, H.Mouzakis, J.Dourakopoulos, P.Giannopoulos.
The entire project is co-funded by the Greek State and EU.