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)).
Twelve piers (forming a square plan) and the pendatives support the dome.
THE MONUMENT IS CONSTRUCTED IN A HIGHLY SEISMIC AREA

Earthquakes (Ms>6) that have affected the Monastery

<table>
<thead>
<tr>
<th>Year</th>
<th>Ms</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1837</td>
<td>6.2</td>
<td>Hydra</td>
</tr>
<tr>
<td>1853</td>
<td>6.8</td>
<td>Thiva</td>
</tr>
<tr>
<td>1858</td>
<td>6.7</td>
<td>Corinth</td>
</tr>
<tr>
<td>1876</td>
<td>6.1</td>
<td>Corinth</td>
</tr>
<tr>
<td>1887</td>
<td>6.3</td>
<td>Corinth</td>
</tr>
<tr>
<td>1891</td>
<td>6.3</td>
<td>Kythnos</td>
</tr>
<tr>
<td>1894</td>
<td>7.0</td>
<td>Athens</td>
</tr>
<tr>
<td>1928</td>
<td>6.3</td>
<td>Corinth</td>
</tr>
<tr>
<td>1938</td>
<td>6.0</td>
<td>Attica</td>
</tr>
<tr>
<td>1948</td>
<td>6.4</td>
<td>Spetses</td>
</tr>
<tr>
<td>1981</td>
<td>6.7</td>
<td>Corinth</td>
</tr>
<tr>
<td>1981</td>
<td>6.4</td>
<td>Boeotia</td>
</tr>
<tr>
<td>1981</td>
<td>6.4</td>
<td>Boeotia</td>
</tr>
<tr>
<td>1999</td>
<td>5.9</td>
<td>Athens</td>
</tr>
</tbody>
</table>

A monument that has sustained many damages and numerous interventions

DOCUMENTED: Historical pathology
CONSTRUCTION PHASES - HISTORICAL PATHOLOGY AND MORE RECENT INTERVENTIONS

Three construction phases

1890-1891 Demolition of the original dome (criticism)
Removal and replacement of mosaics by Italian conservators (NOVO, 1890-1897). Use of hydraulic lime

Use of cement in the more recent interventions
Rather minor damages to the mosaics due to the 1981 earthquake—No measures were taken
The coloured parts are reconstructed.
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).
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
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)
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.
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.

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

<table>
<thead>
<tr>
<th>Wallette</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
<th>$\varepsilon_v$ ($0'/00$)</th>
<th>$E_0$ (GPa)</th>
<th>$E_0/\sigma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.82</td>
<td>*</td>
<td>1.0</td>
<td>594.45</td>
</tr>
<tr>
<td>2</td>
<td>1.74</td>
<td>-1.6</td>
<td>1.44</td>
<td>827.59</td>
</tr>
<tr>
<td>3</td>
<td>2.26</td>
<td>-2.25</td>
<td>1.5</td>
<td>663.72</td>
</tr>
</tbody>
</table>

(*) Unreliable measurements of some of the LVDTs

**Wallettes in diagonal compression**

[Graph showing stress-strain relationship for different wallettes]
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.
Drilling of holes and installation of plastic tubes

Drilling holes

Sealing cracks

Installing tubes

Holes at distances $0.5 - 1.0 \text{m} \leq \text{thickness of masonry} + \text{along cracks}$

Holes deep enough to reach filling material

Transparent tubes (1.0 to 10.0 mm)

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

<table>
<thead>
<tr>
<th>Wallette</th>
<th>$f_{w0}$ (MPa)</th>
<th>$f_{ws}$ (MPa)</th>
<th>$f_{ws}/f_{w0}$</th>
<th>$\varepsilon_{v0}$ (%)</th>
<th>$\varepsilon_{vs}$ (%)</th>
<th>$E_0$ (MPa)</th>
<th>$E_s$ (MPa)</th>
<th>$E_s/E_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.82</td>
<td>3.00</td>
<td>1.65</td>
<td>*</td>
<td>-1.76</td>
<td>1,000</td>
<td>1,200</td>
<td>1.20</td>
</tr>
<tr>
<td>2</td>
<td>1.74</td>
<td>3.75</td>
<td>2.16</td>
<td>-1.6</td>
<td>-2.50</td>
<td>1,440</td>
<td>1,550</td>
<td>1.08</td>
</tr>
<tr>
<td>3</td>
<td>2.26</td>
<td>3.73</td>
<td>1.65</td>
<td>-2.25</td>
<td>-3.39</td>
<td>1,500</td>
<td>1,300</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Graphs**

- **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.
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**

<table>
<thead>
<tr>
<th>No. of test</th>
<th>Excitation of test</th>
<th>Direction of excitation</th>
<th>Amplification of original record</th>
<th>Amplification of original record</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>White-noise</td>
<td>X</td>
<td>30%</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>White-noise</td>
<td>Y</td>
<td>50%</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>White-noise</td>
<td>Z</td>
<td>Application of vertical load</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>75%</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>Irpinia earthquake</td>
<td>Y</td>
<td>100%</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>150%</td>
<td>X-Y</td>
</tr>
<tr>
<td>7</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>200%</td>
<td>X-Y</td>
</tr>
<tr>
<td>8</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>250%</td>
<td>X-Y</td>
</tr>
<tr>
<td>9</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>300%</td>
<td>X-Y</td>
</tr>
<tr>
<td>10</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>350%</td>
<td>X-Y</td>
</tr>
<tr>
<td>11</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>400%</td>
<td>X-Y</td>
</tr>
<tr>
<td>12</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>450%</td>
<td>X-Y</td>
</tr>
<tr>
<td>13</td>
<td>Irpinia earthquake</td>
<td>X</td>
<td>500%</td>
<td>X-Y</td>
</tr>
<tr>
<td>14</td>
<td>Sine sweep</td>
<td>X</td>
<td>100%</td>
<td>X</td>
</tr>
<tr>
<td>15</td>
<td>Sine sweep</td>
<td>Y</td>
<td>150%</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Notes:**
- Tests 13 to 20 are highlighted to indicate earthquake excitation.
- Tests 16 to 20 are shaded to denote higher amplification levels for earthquake excitation.
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, reconstruction, etc.)
Completed, 2007

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

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
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**

- **Accelerometers**: 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).
- Residual deformation along the N-S direction

- **Increase** of the eigenfrequency, **reduction** of the period of vibration and **reduction** of the damping
2\textsuperscript{ND} 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

Equivalent static analysis

THE ENTIRE MONUMENT

Equivalent static analysis

and

Time-history analyses
The data were used for the calibration of the models.
EIGEN-FREQUENCIES

f3=5.07Hz

f3=5.08Hz

f4=5.93Hz

f4=5.42Hz

MODEL

1ST MODE

1ST MODE

RECORDING OF EARTHQUAKES

2ND MODE

2ND MODE
RESPONSE OF THE MODEL

RESPONSE TO THE SEISMIC EVENT

CALIBRATION OF MODELS

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

Recorded at the base of the cupola-East
REPRODUCTION OF OBSERVED DAMAGES-PENDATIVES-ARCHES

MAXIMUM TENSILE STRESSES FOR THE BEARING SYSTEM BEFORE INTERVENTIONS
REPRODUCTION OF OBSERVED DAMAGES

NW pendative

Main east-arch
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
New steel stiffening frames in the openings of the drum
Diaphragms at the extrados of domes and vaults & diaphragm at the exo-narthex

Steel diaphragms+timber pavement

Timber diaphragm and pavement

Steel diaphragms
Steel diaphragms with timber pavement or without pavement

Timber floor and pavement

Diaphragm at the western part
INTERVENTIONS

- Steel jackets of piers
- Ties/West wall
- Ties/Struts-Narthex
- Ties/Struts-main church
View of the monument after intervention
View of the monument after intervention
INTERVENTIONS

MOST OF THEM - INVISIBLE
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.