NIKER WORKSHOP

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# MALLORCA CATHEDRAL

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NEW INTEGRATED KNOWLEDGE BASED APPROACHES TO THE PROTECTION OF CULTURAL HERITAGE FROM EARTHQUAKE INDUCED RISK

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# MALLORCA CATHEDRAL

## OBJECTIVES

- Seismic assessment of a vulnerable building in a moderate seismic place
- Preparation and validation of numerical model
- Characterization on influence of environmental parameters (temperature) on dynamic parameters
- Try a monitoring approach combining continuous thermographic and dynamic monitoring (alongside dynamic identification)
- Seismic assessment
- Proposal and validation of upgrading solution
- Contribute to validate project methodology and technologies
- Final remarks

# MALLORCA CATHEDRAL

Total length 121 m, total width 55 m
Central nave: 44 m high, 17.8 m wide
Lateral naves: 29 m high, 9 m wide
Limestone masonry and lime mortar

Piers with octagonal section
(1.5÷1.7 m circumscribed diameter),
22.7 m high (slenderness ratio 14.2)

**Construction**: 1306-1600
long interruption period (1460-1560)

Repair interventions, especially during the 18$^{th}$ and 19$^{th}$ centuries

(4$^{th}$ vault partially collapsed 30 years after the construction, repairs of many vaults, dismantlement of Renaissance façade in 1851 due to 1.3 m out-of-plumb)

Case studies

# MALLORCA CATHEDRAL

Case studies

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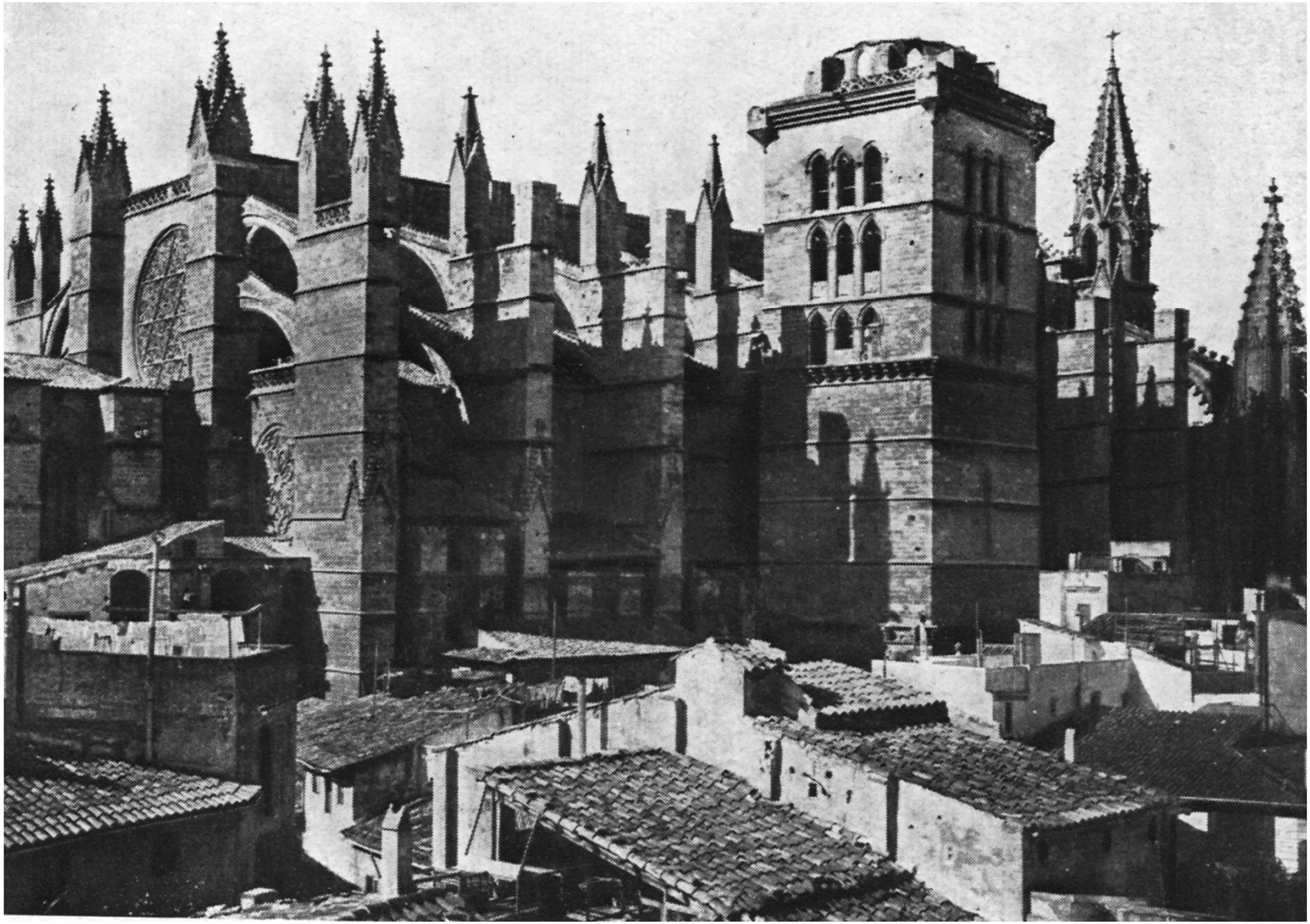

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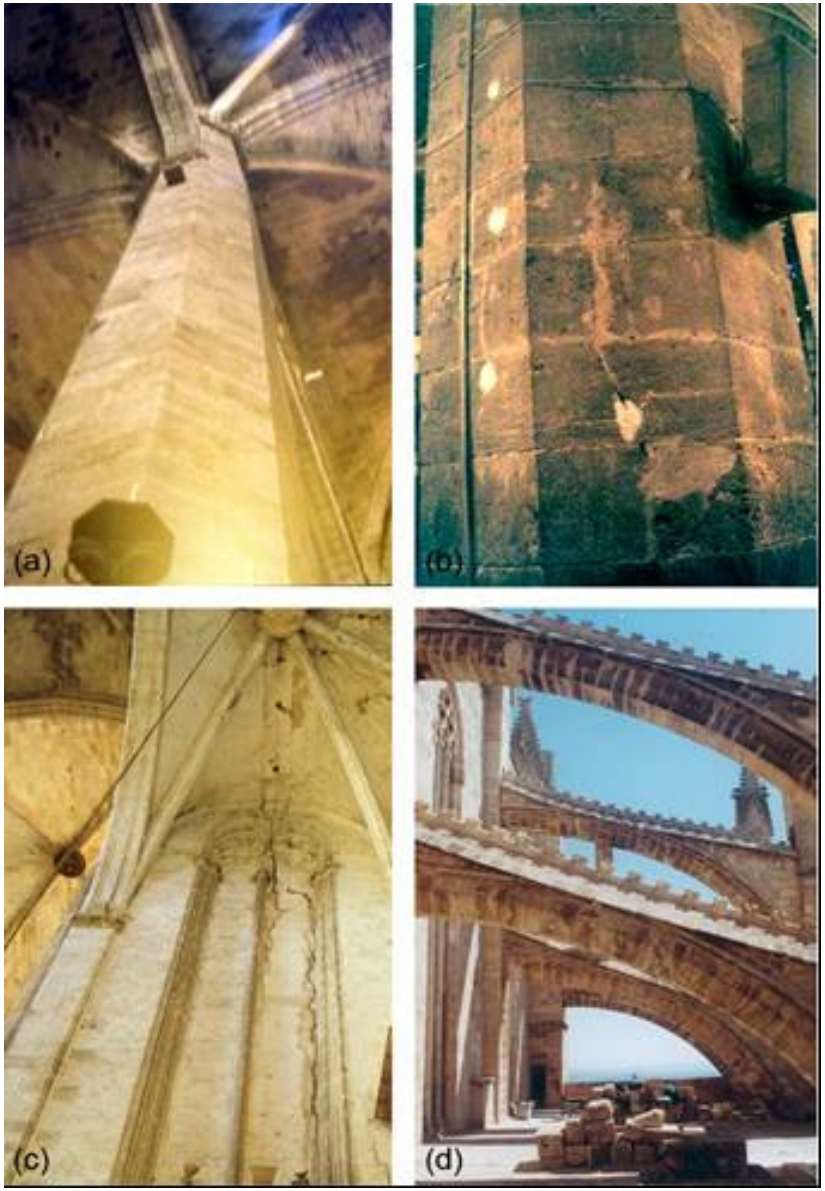
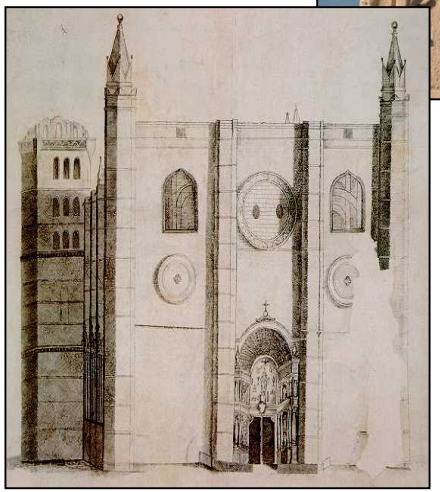


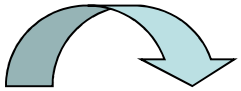

a) Large lateral deformations of the slender piers (even 1/90 H). The deformation is progressing at a rate of **0.1 mm per year** (monitoring from 9/2003 to 9/2008)

b) Cracks at the base of some piers (stable)

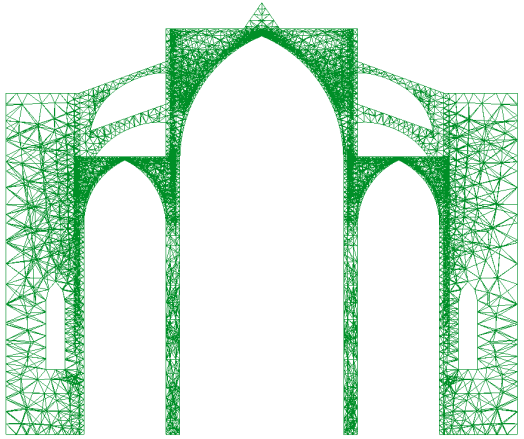
c) Cracks in buttresses following the perimeter of false windows

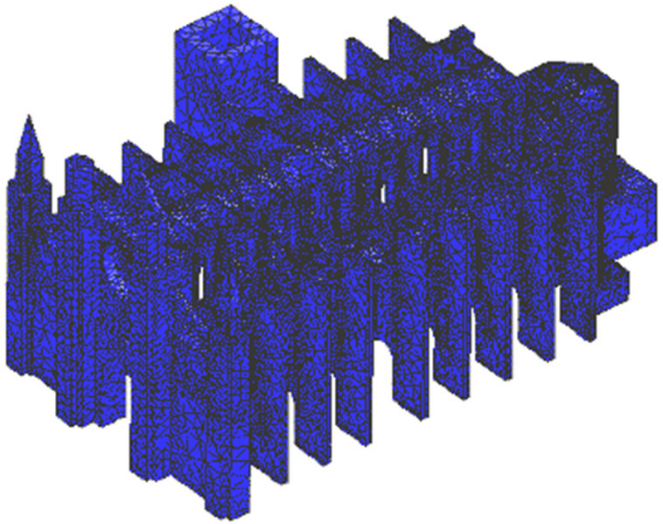
d) Deformation of flying arches

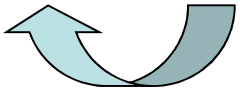




Input data provided by survey and
Experiments carried out as part of inspection







Calibration by comparison with experimental
measurements

Case studies

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## TECHNIQUES

- NDT inspection. Dynamic Identification
- Continuous dynamic monitoring (CDM)
- Thermographic monitoring
- FEM nonlinear analysis
- Model updating based
- Seismic assessment (pushover analysis)
- Simulation of strengthening solutions

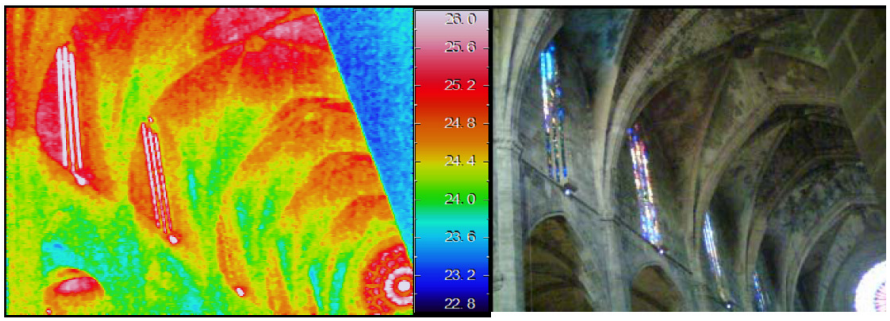
## RESULTS

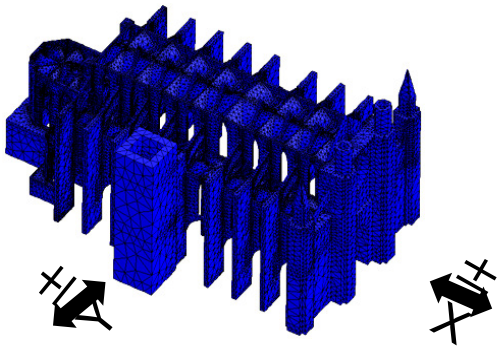
•Study of influence of temperature on natural frequencies. Method combining DI and CDM for modal updating.

•Seismic assessment of vulnerable building in moderate seismic place.

•Identification of strengthening needs.

•Proposal of alternative solutions and identification of optimal one (tying).



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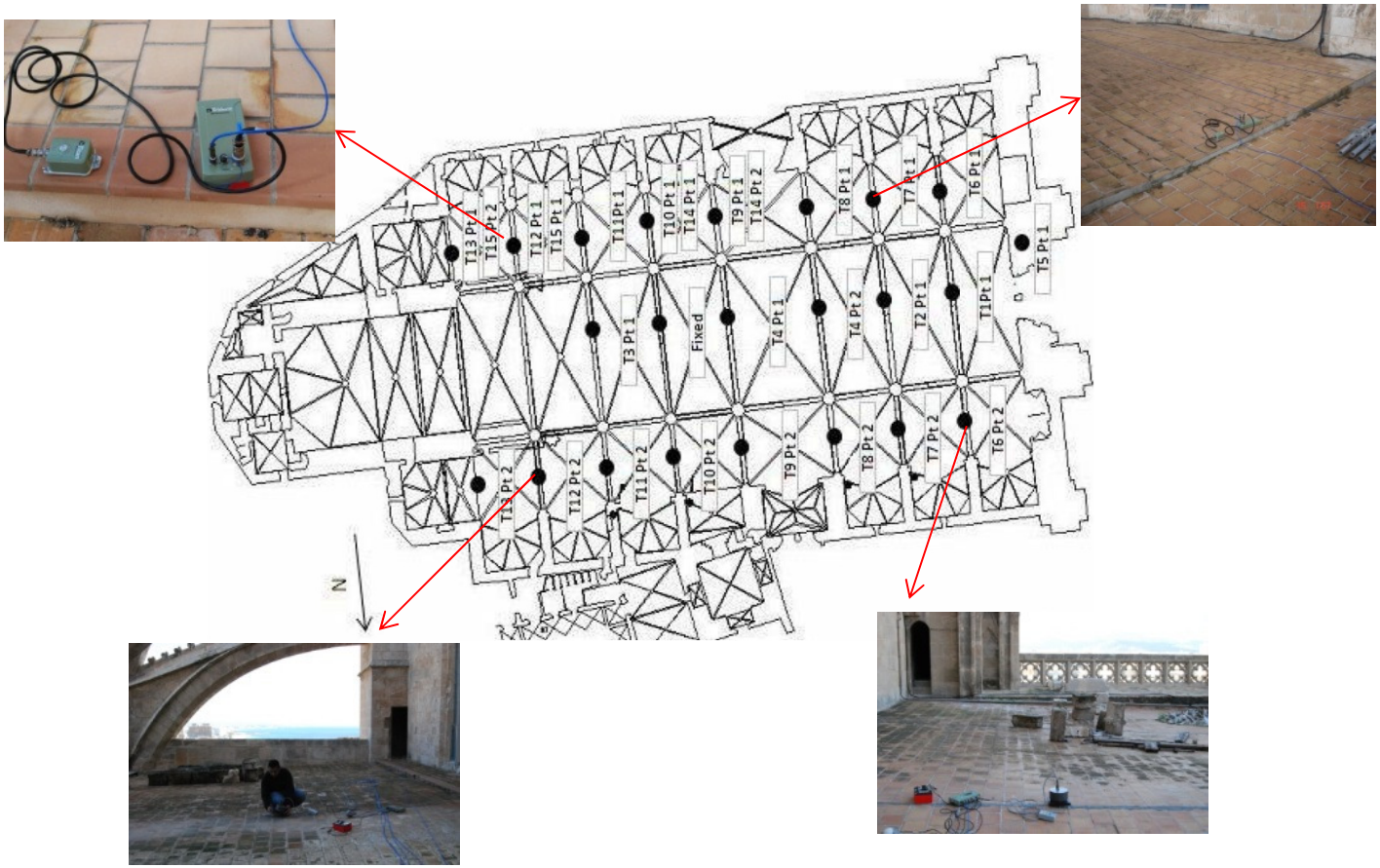
## DYNAMIC IDENTIFICATION

Carried out on 15&16-12-2010 using three tri-axial accelerometers in 15 different setups.



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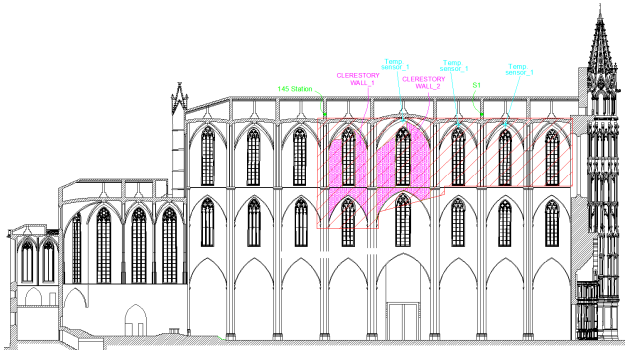
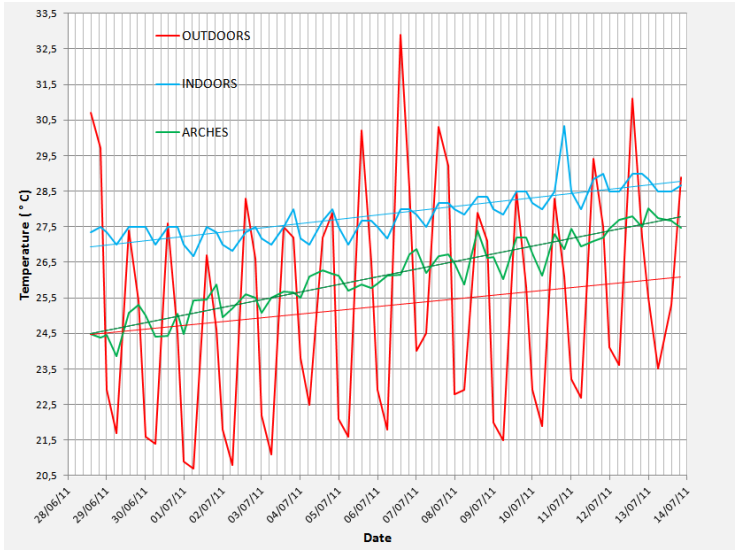
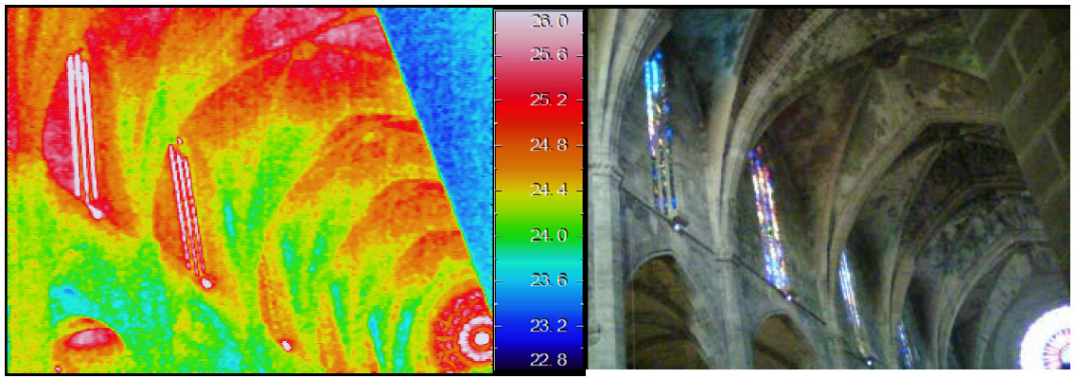
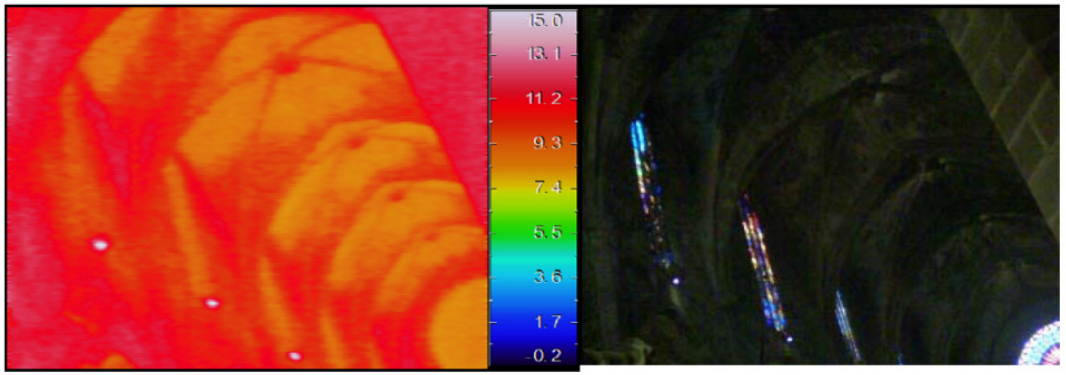
## THERMOGRAPHIC MONITORING






Summer




Winter

# Examples of adopted techniques

## CONTINUOUS DYNAMIC MONITORING

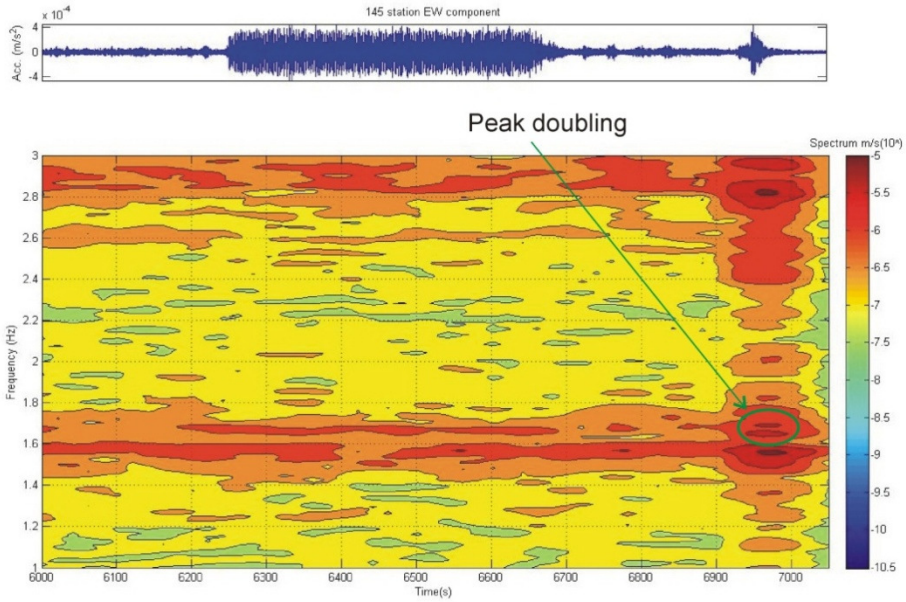
### Purpose

Continuously measure, record and also wirelessly transfer the records of the acceleration of some selected points using tri-axial accelerometers, during long periods of time.

### Application

Identification of dynamic response during micro-tremors or far epicenter earthquakes in moderate seismic places.

Correlation with environmental parameters (temperature)
Study of the influence of damage
Model updating.
Early warning
Assessment and control after intervention

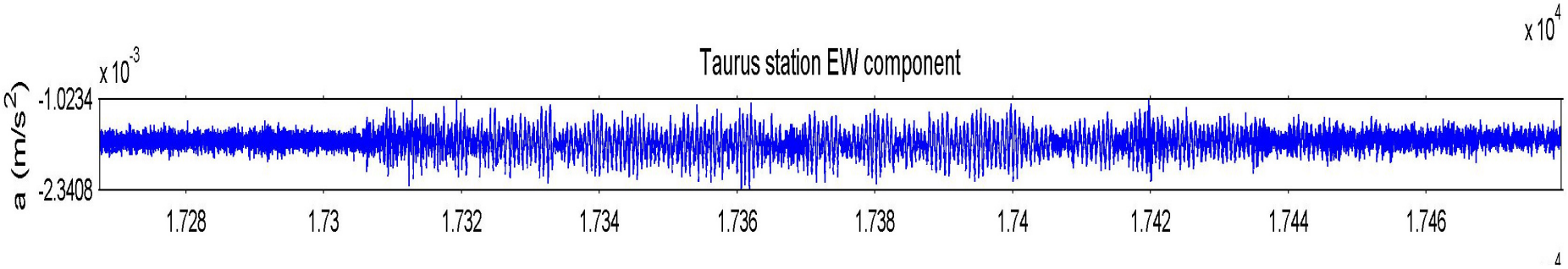


Case studies

# MALLORCA CATHEDRAL

| Location and date | Magnitude | Distance km | NS Acc. mm/s2 | EW Acc. mm/s2 | Up Acc. mm/s2 |
|---|---|---|---|---|---|
| Calm day | | | 0.135 | 0.154 | 0.253 |
| Windy day (*) | | | 0.53 | 0.54 | 0.57 |
| Menorca August 1, 2011 | 2.7 | 145 | 0.41 | 0.45 | 0.375 |
| Lorca May 11, 2011 | 5.1 | 400 | 2.73 | 2.34 | 1.52 |
| Great East Japan March 11, 2011 | 9.0 | 7100 | 0.294 | 0.518 | 0.45 |

(*) Max=21.1 mm/s2 on 24 March 2011




The values of the first natural frequencies are in average of 1.36 Hz, 1.47Hz, 1.59 Hz and 1.94 H.

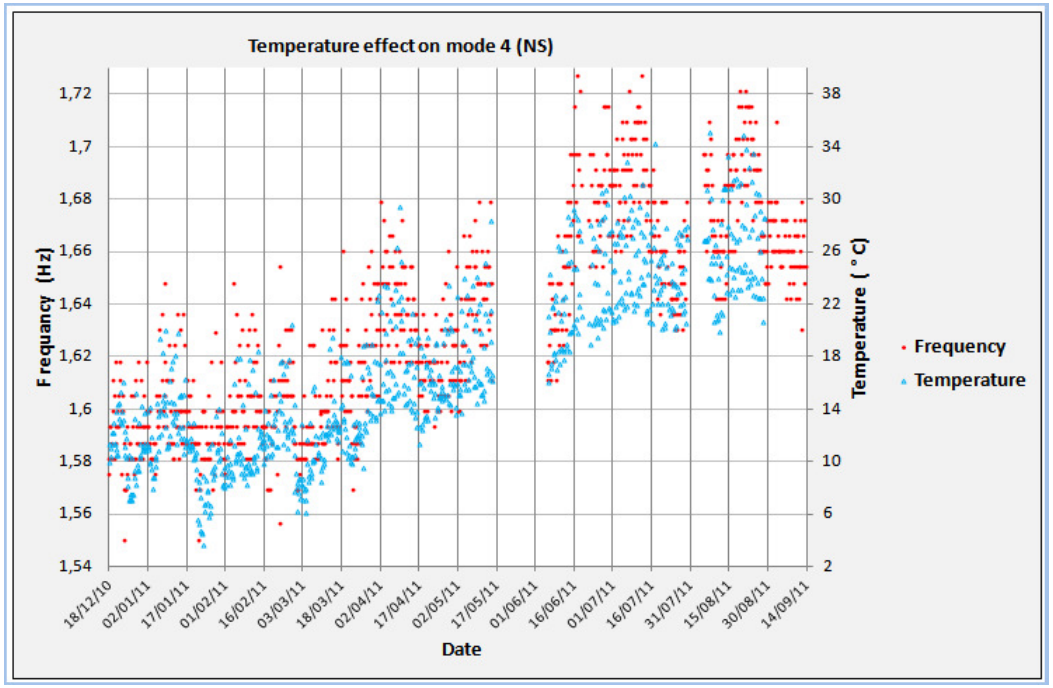
# MALLORCA CATHEDRAL

## DYNAMIC MONITORING

• The system worked properly from 17-12-2010 to 13-9-2011
Another monitoring period started in 18-5-2012 and is still working

• Good correlation between frequency and temperature.

• Temperature variation resulted in a measurable change in natural frequencies of at least 11%.




| Mode no. | Maximum | Minimum | (Max.-Min.) % (Max.) |
|---|---|---|---|
| 2 | 1.636 | 1.404 | 14 |
| 3 | 1.709 | 1.495 | 13 |
| 4 | 1.740 | 1.540 | 11 |
| 8 | 3.048 | 2.621 | 14 |

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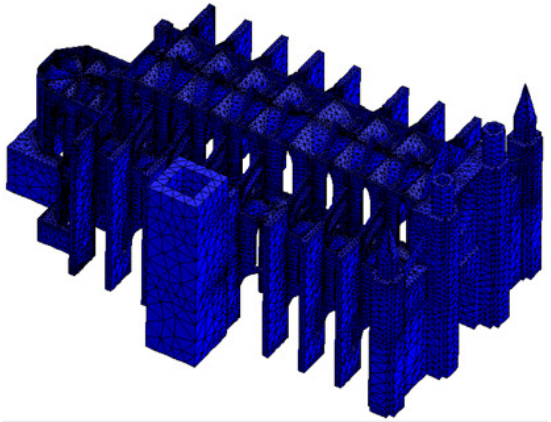
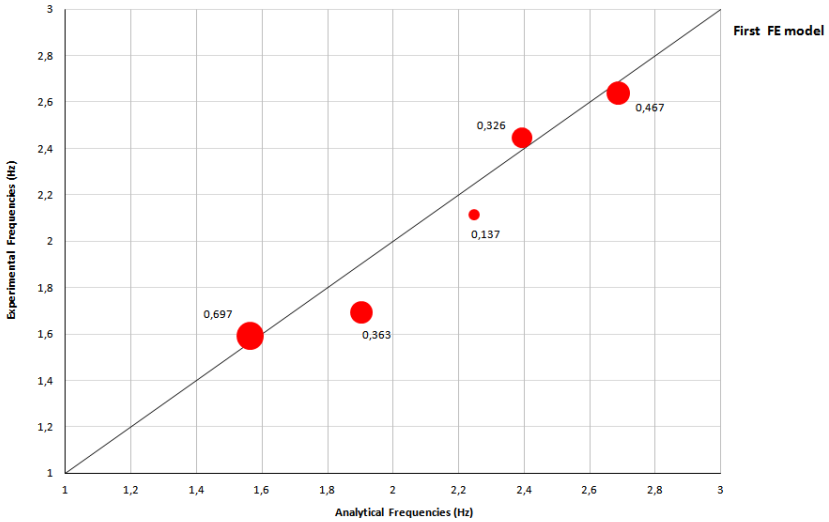
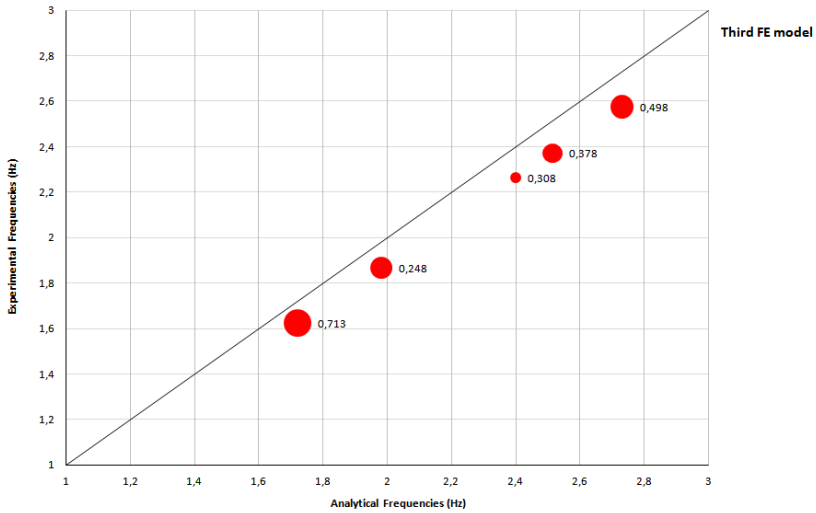
## MODEL UPDATING

- Influence of material properties investigated
- The influence of damage (large cracks is now into study)





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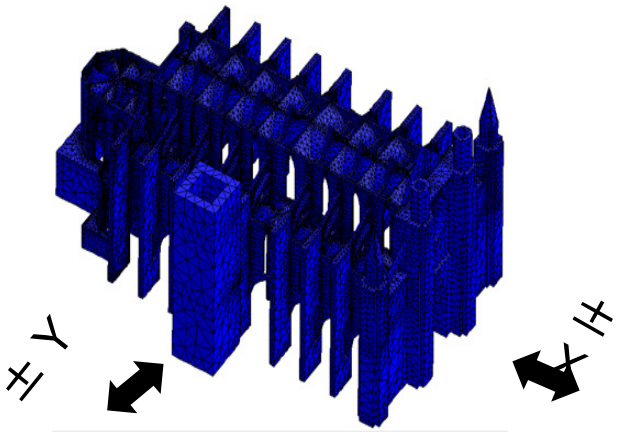
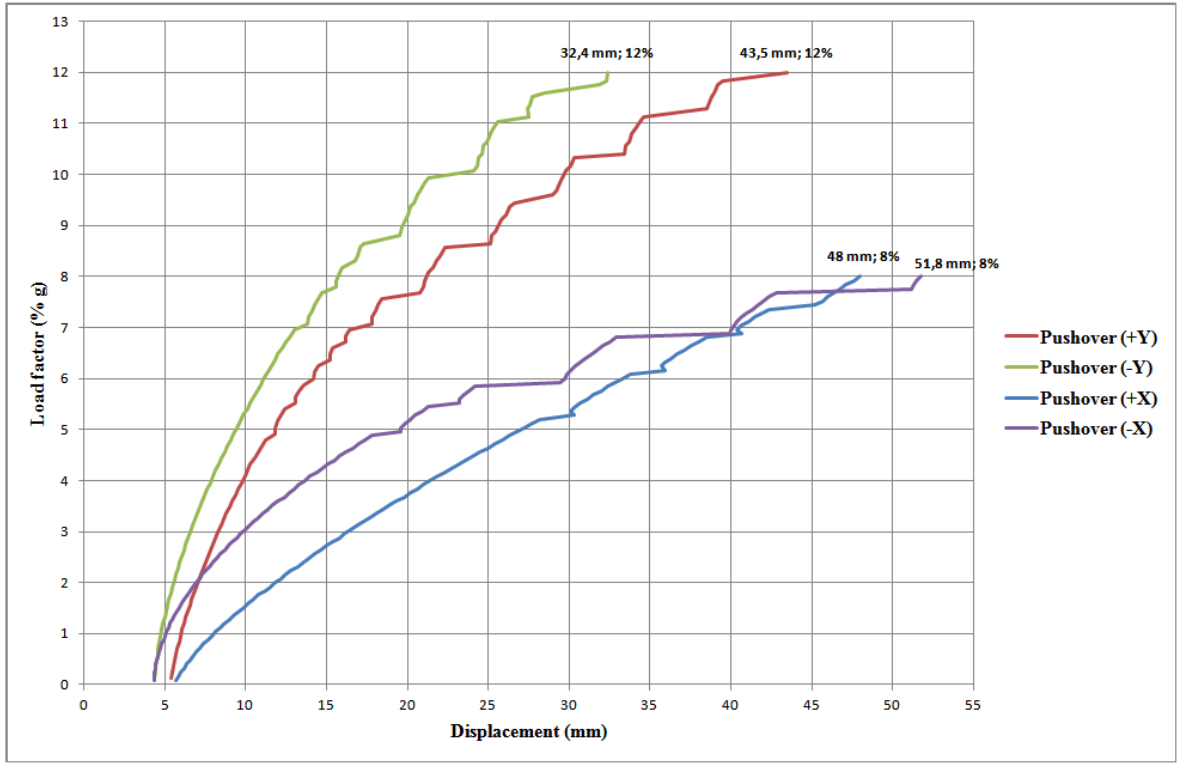
## SEISMIC ANALYSIS

Nonlinear static pushover analysis
Tensile regime: smeared cracking with multi-directional fixed crack model
Compressive regime :isotropic plastic Drucker-Prager model



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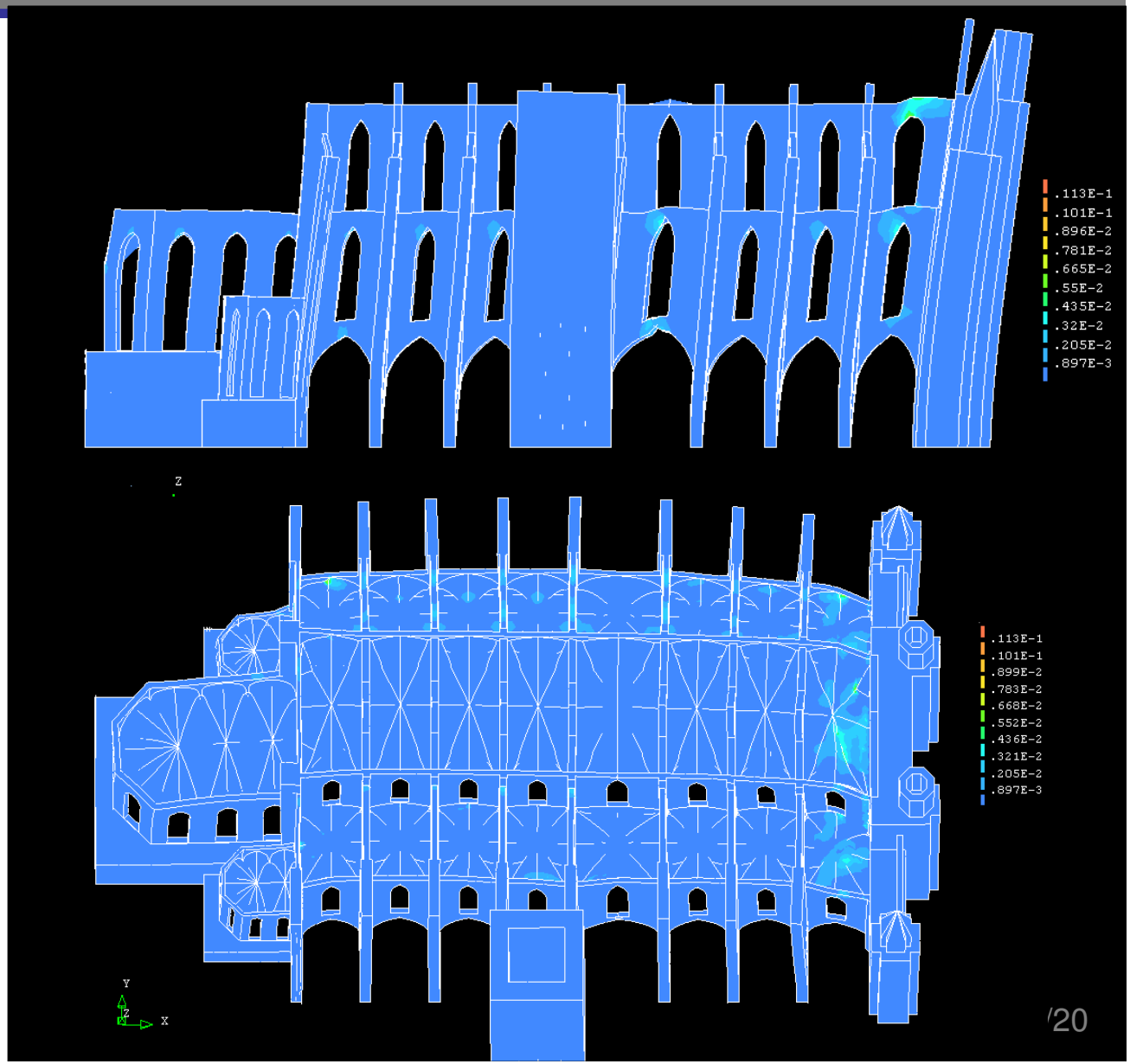
Ultimate condition

***Longitudinal***

***Transverse***



# MALLORCA CATHEDRAL

## INTERVENTION PROPOSAL

Study of alternative solutions

| Piers | Walls and buttresses | Connection / deformation control of main members in the longitudinal direction. (East façade- west façade and nave) | Connection / deformation control of main members in transverse direction |
|---|---|---|---|
| **Leave as it is / only maintenance works** | Leave as it is / only maintenance works | Leave as it is / only maintenance works | **Leave as it is / only maintenance works** |
| Deep repair of cracks (injection / gruting) | **Deep repair of cracks (injection / gruting)** | **Longitudinal ties (partial or continuous). 1 level** | Transverse ties at the level of vault springings (interior) |
| Confinement at the base of piers | Vertical prestressing of piers | Longitudinal ties (partial or continuous). 2 levels | Transverse ties over vaults |

## PROPOSED SOLUTION

- **G*en*eral maintenance** works including, in particular, the **repointin**g of joints showing deteriorated mortar or loss of material.

- **Deep grouting or injection** (depending of crack width) of major cracks existing in clerestory walls and buttresses. In cases with only superficial repair, the sealing material will have to be extracted.

- **Implementation of ties** in the longitudinal direction to improve the connection between the east and west façades and the nave (1 level)

- **Monitoring after the intervention** (both static and dynamic) allowing an incremental approach.

Depending of the results of this monitoring, additional strengthening increments mayl be implemented. A second strengthening complementary operation may consist, if necessary, of a second series of ties, to be placed at a different level (close to the springings of the lateral naves).

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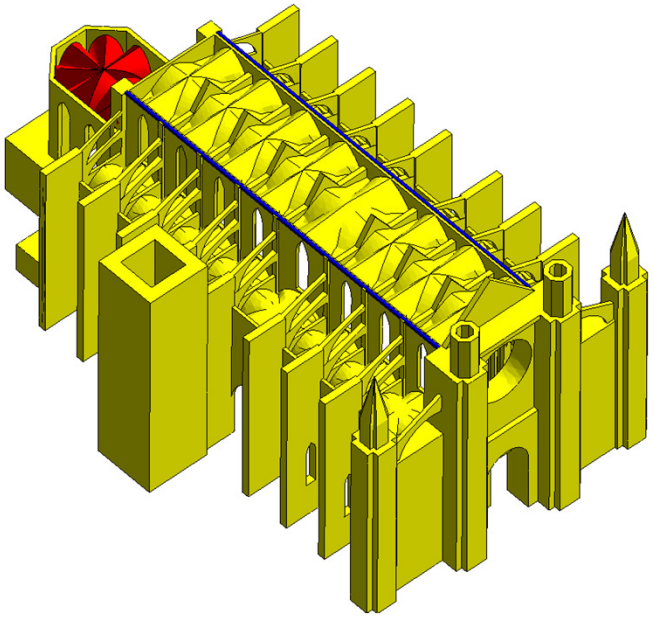

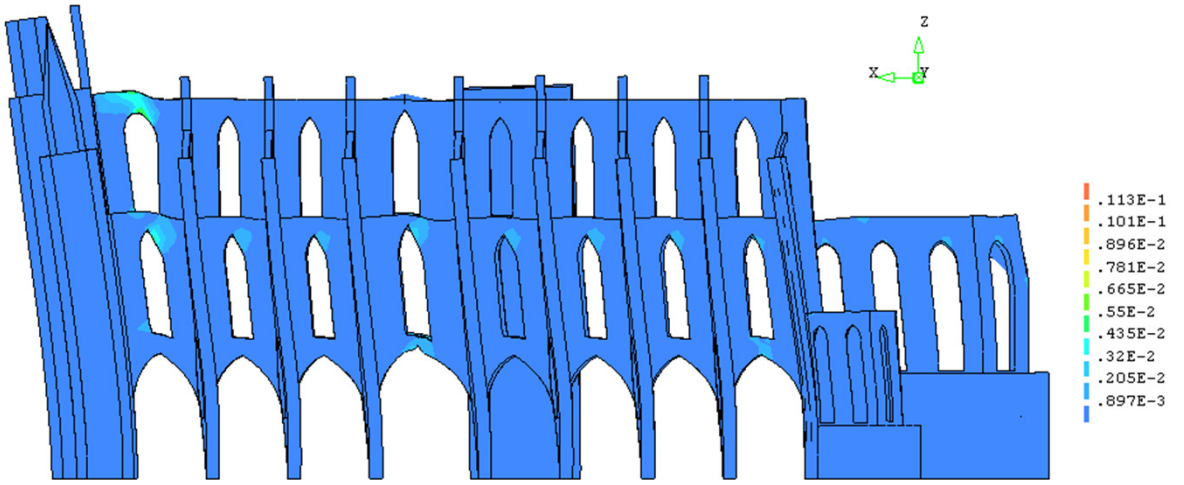


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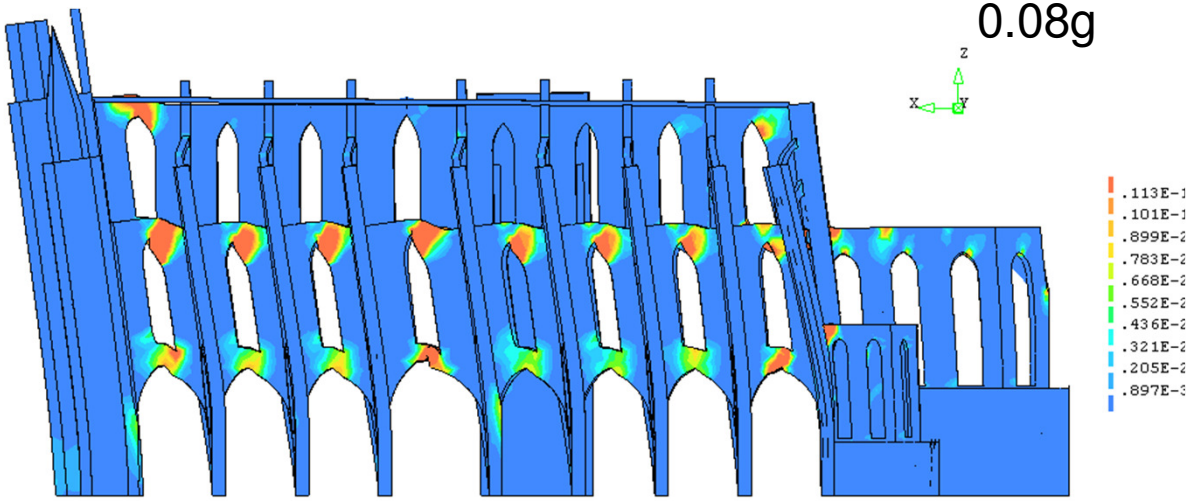


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## FINAL REMARKS

- Vulnerable structure  in moderate seismic location
- Need for validating numerical model based on monitoring
- Significant variation of frequencies with temperature
- “Peak doubling” and other effects detected possibly related to damage
- Possibility of significant improvement by means of a  “light” strengthening