COST TU1402: Quantifying the Value of Structural Health Monitoring
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The Value of SHM for the Structural Behaviour of Masonry Structures under Varying Environmental Effects

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Contents

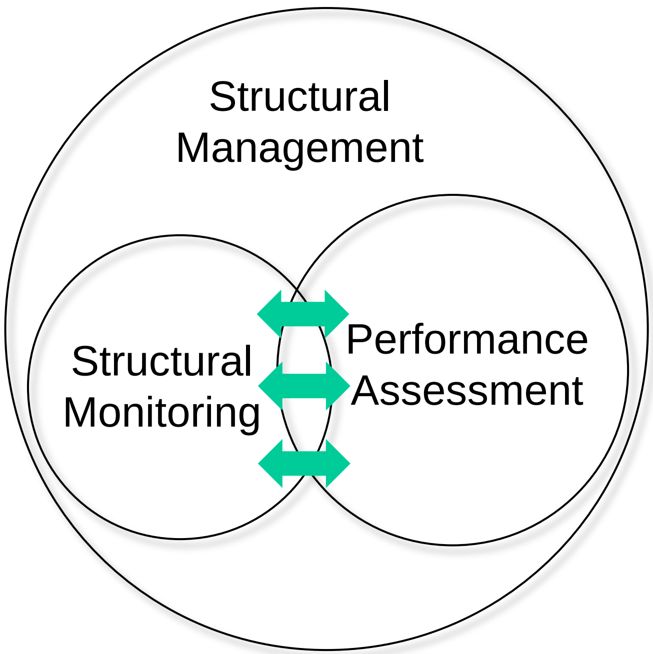
- ❑ Scope & Focus of the Work
- ❑ General Framework
- ❑ Case Study
- ❑ Identification & Track of KPIs
- ❑ Warning Levels and Thresholds
- ❑ Final Remarks & Conclusions

Scope and Focus

Why is **structural health monitoring** important?

- Keep under control the system’s health
- Identify the damage at the earliest stage
- Adopt condition-based maintenance strategies
- Design remedial measures in a timely fashion
- Ensure life-safety standards

Medicine vs Engineering



General Framework

Structural System

- Buildings
- Bridges
- Architectural heritage
- Towers/Chimneys
- Offshore structures
- Dams

Inspection & Data Acquisition

- Historical investigation
- Condition survey
- Visual inspection
- On site & lab testing
- Short-term observations

Key Performance Indicators

- Crack widths
- Tilting
- Natural frequencies
- Mode shapes
- Stress ranges
- Strains

Diagnosis

- SHM
- Track of KPIs
- Environmental variability
- Threshold conditions
- Warning levels

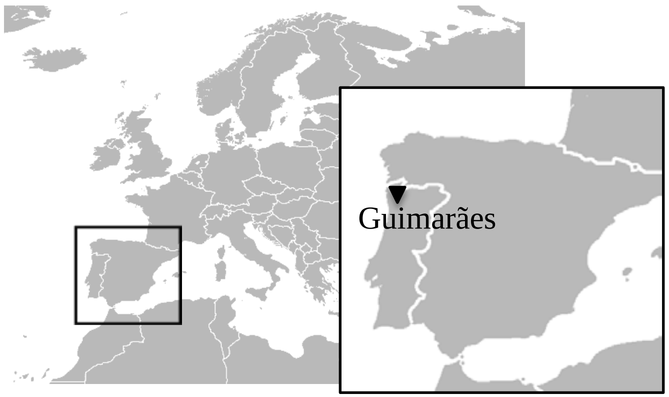
Performance Assessment

- Deviation from target behaviour
- Repeated anomalies
- Quantification of changes
- Serviceability
- Ultimate/Limit state

Structural Management

- Forecasting
- Inspection/Verification
- Maintenance
- Minimal intervention
- Repair/Strengthening

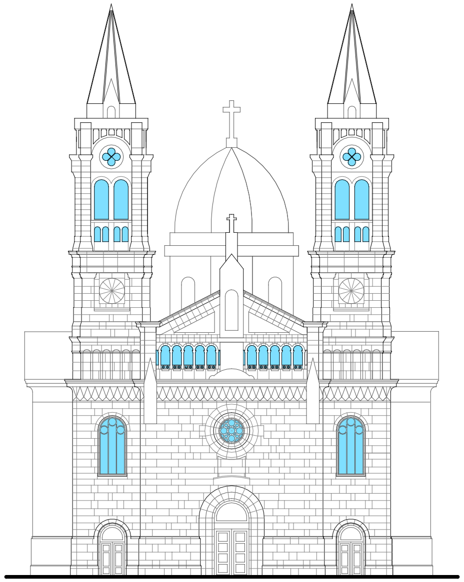
Case Study (I)

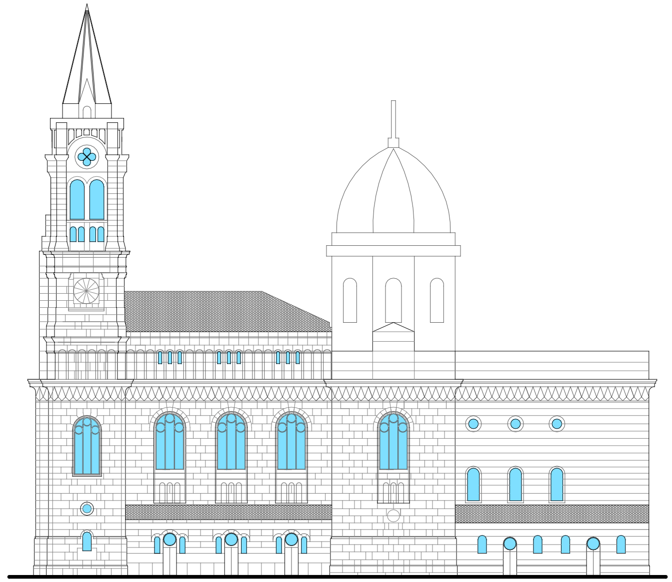


Church of Saint Torcato

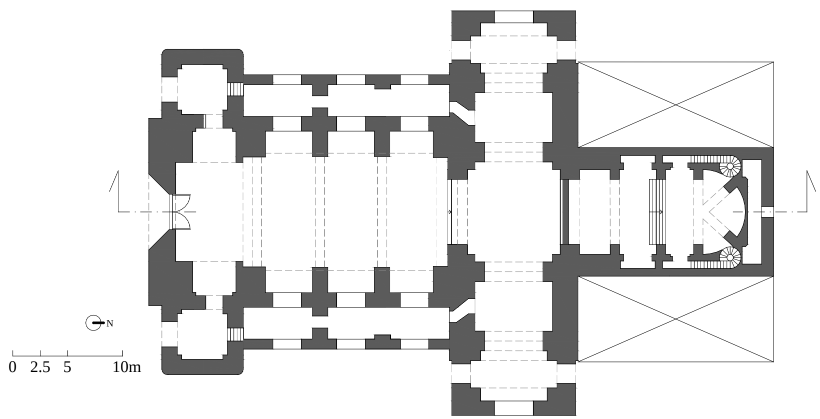
- Portuguese architectural heritage
- Hybrid-style temple
- 1825 → two centuries of construction
- 3 different architects

Case Study (II)

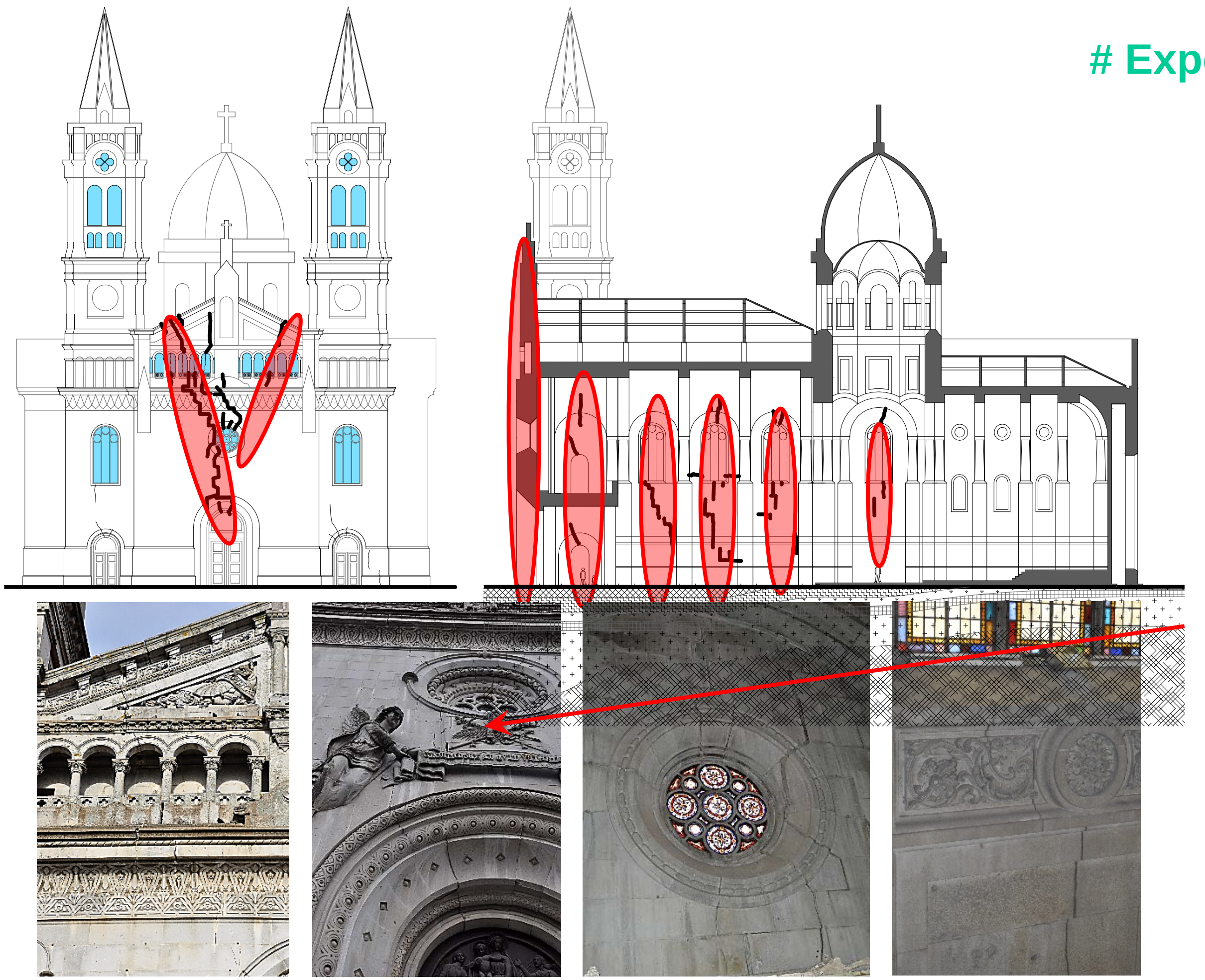




- ❑ Longitudinal plan
- ❑ Nave + Transept
- ❑ Gabled façade
- ❑ Spired towers



Case Study (III)



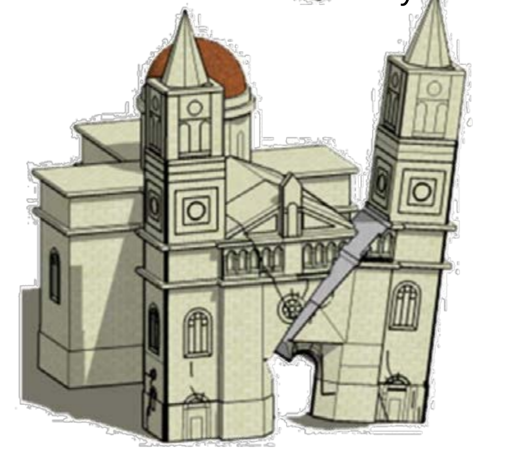
Experimental Campaign (1998)

- V-cracking pattern (façade)
- Vertical cracks (sidewalls)
- Towers tilting (long. & trans.)
- Differential soil settlements

→Heterogeneous soil profile

→Presence of non-cohesive soil layers

→Distance from the bedrock layer



Identification & Track of KPIs (I)

Façade

Critical Factors ⬌ Key Performance Indicators

- ❑ Crack width & opening rate:

The cracking pattern can be active or dormant. Active or working cracks may open or close, but dormant cracks have stopped moving. The easiest way to detect active cracks is to record both their width and growth rate at regular time intervals.

- ❑ Towers tilting rate:

The progressive increase of tilting may not only drive the foundation system to failure, but may also produce high compressive stresses in the towers walls. It is important to monitor the towers tilting rate over time and to identify threshold value conditions for the definition of warning levels.

- ❑ Correlation with ambient parameters:

Changing environmental conditions can adversely influence the structural performance of historical buildings due to the porosity of the masonry material (e.g. temperature/moisture changes that continually cause the crack to open and close).

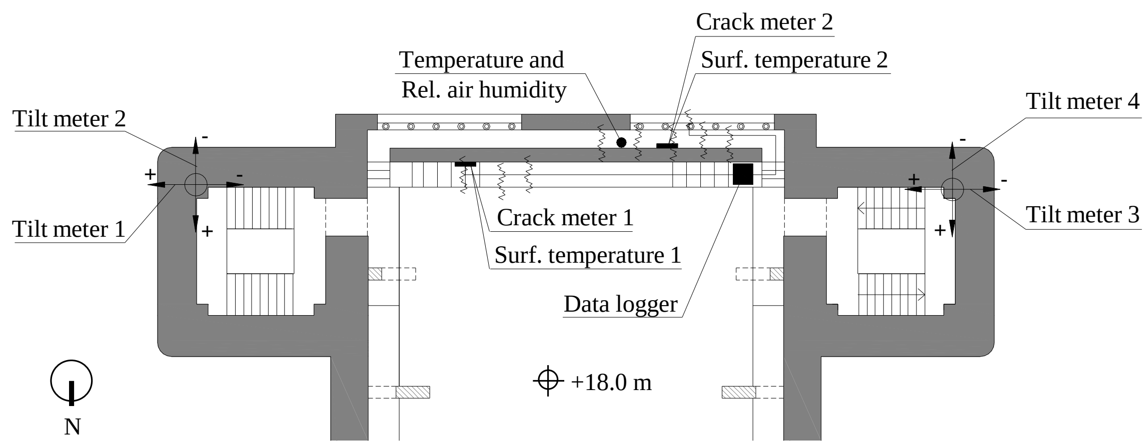
Identification & Track of KPIs (II)

What are **KPIs**?

Why are **KPIs** important?

How can **KPIs** be tracked?

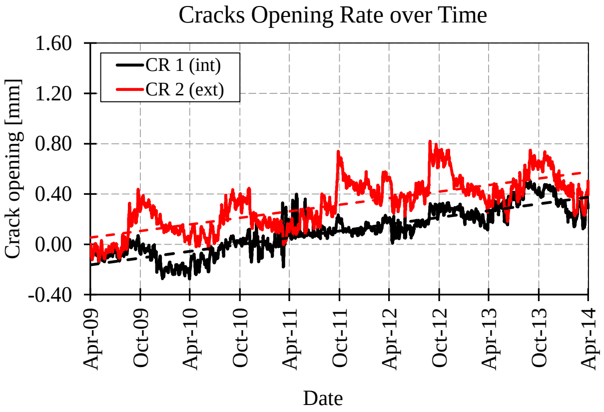
- Static Monitoring System

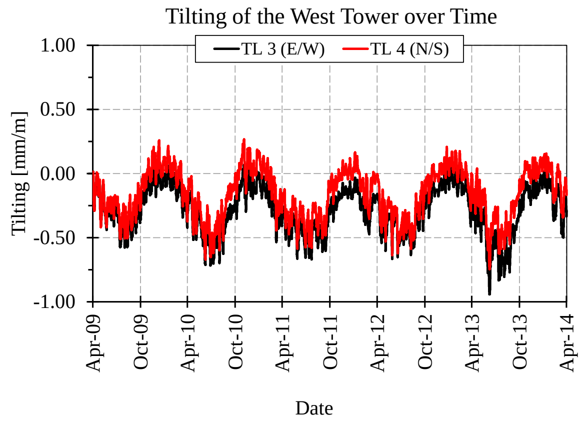


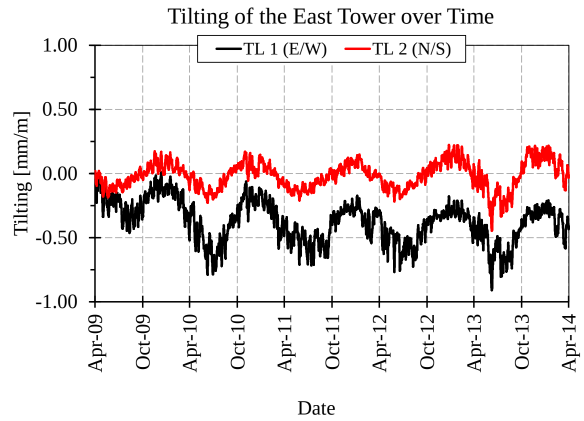
Case-specific quantifiable measurements

- Establish baseline information
- Set performance standards
- Optimise control of structural integrity
- Quantify changes in system's response

Identification & Track of KPIs (III)

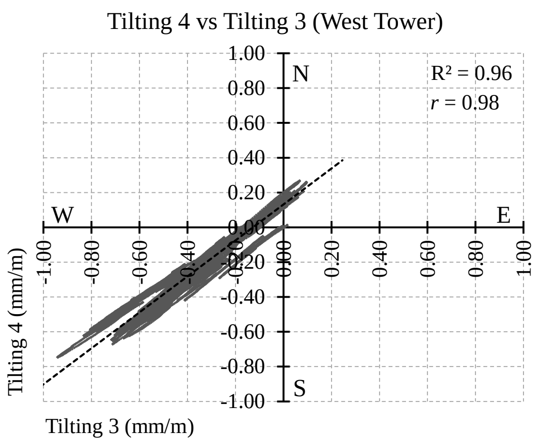


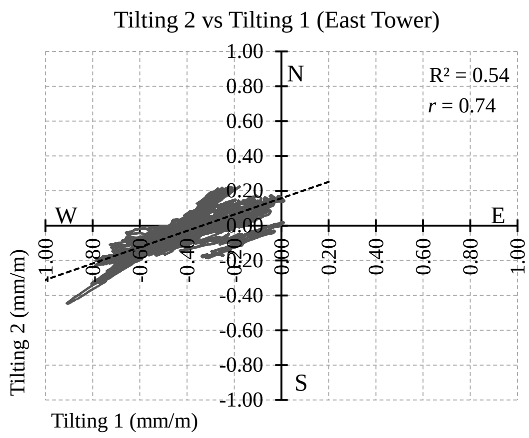




Cracking Pattern:

- Increasing linear trend (0.1 mm/year)
- Growth rate CR2 > CR1



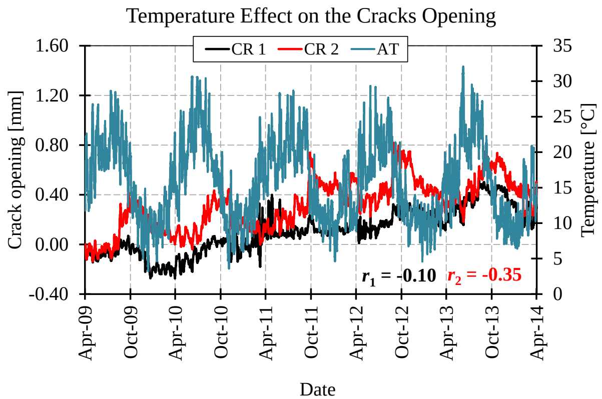


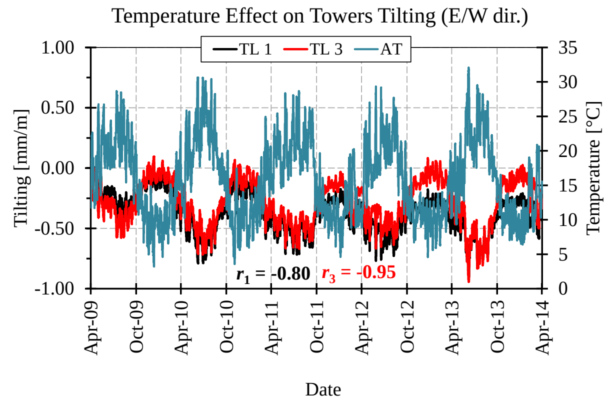
Towers Tilting:

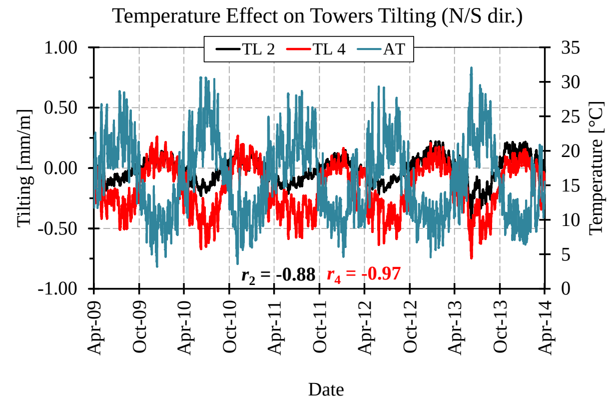
- In-phase cyclic oscillations
- Oscillation amplitudes $TL_{3,4} > TL_{1,2}$
- Max Tilt: 0.94 mm/m (W); 0.74 mm/m (S)
- Trend: West-South leaning

Identification & Track of KPIs (IV)

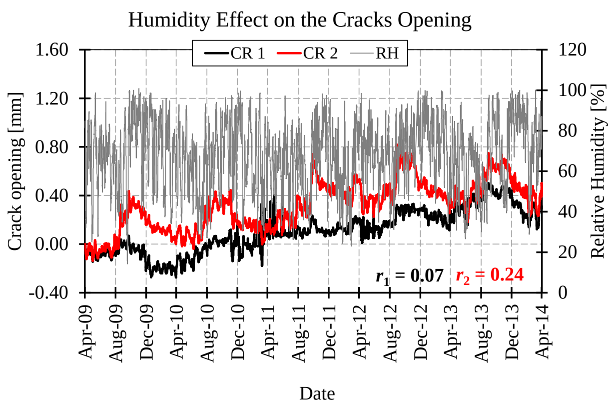
❑ Correlation with Air Temperature

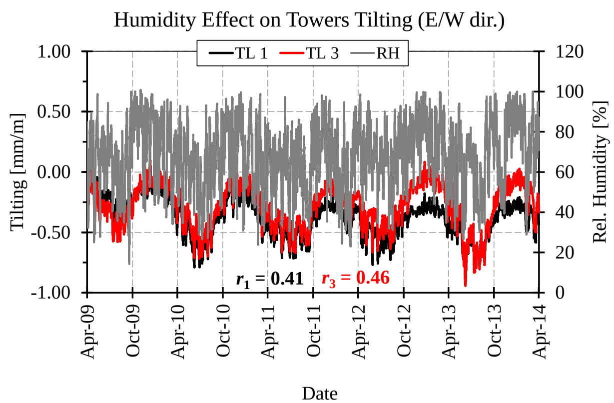


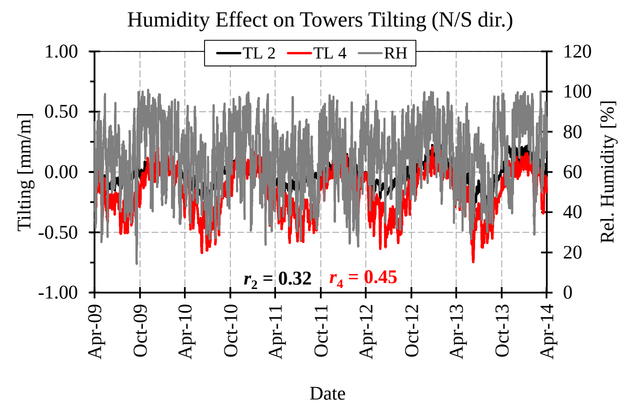




❑ Correlation with Relative Humidity







Warning Levels and Thresholds (I)

 # Cause | Pathology ⟷ Effect | Symptom

Differential soil settlements → Progressive increase of tilting → Decrease of towers stability

Warning level	Criteria	Actions
Level 0 Target behaviour	The structure behaves as expected	• No measures to be taken
Level 1 Warning level	Deviation from the target behaviour, e.g. variation in tilting trend, atypical towers displacement or increase of cracks width	• Verification of the system's behaviour • Design of corrective measures
Level 2 Alarm level	Repeated atypical behaviour, progressive displacement increases, stability problem	• Safety management plan • Immediate intervention measures

In case of **deviation from the target behaviour**, the relevant warning level is issued.

Warning Levels and Thresholds (II)

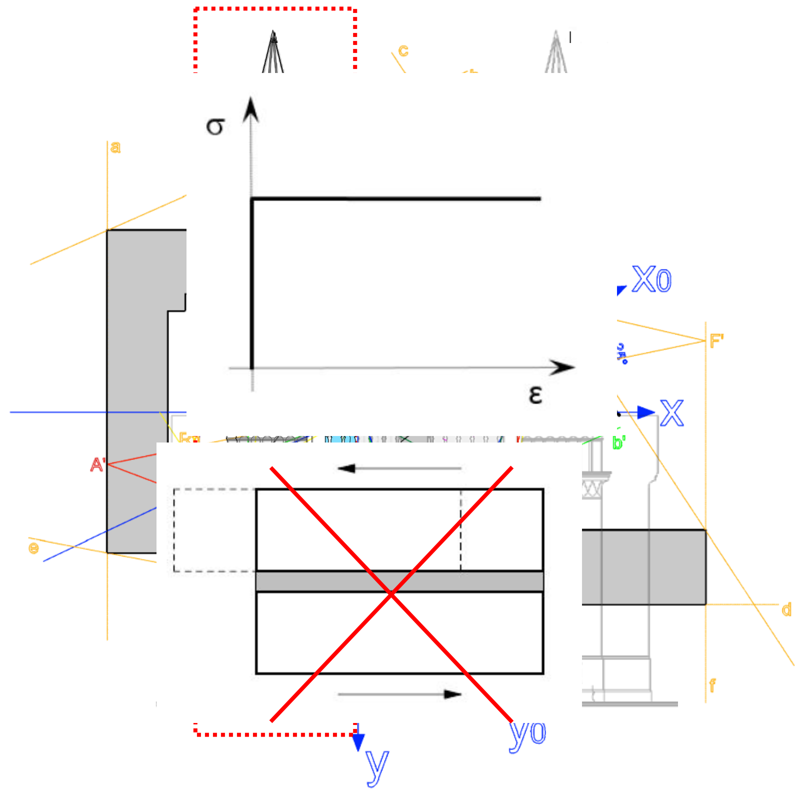
Stability Analysis ⟷ Threshold Value Conditions

Western Tower:

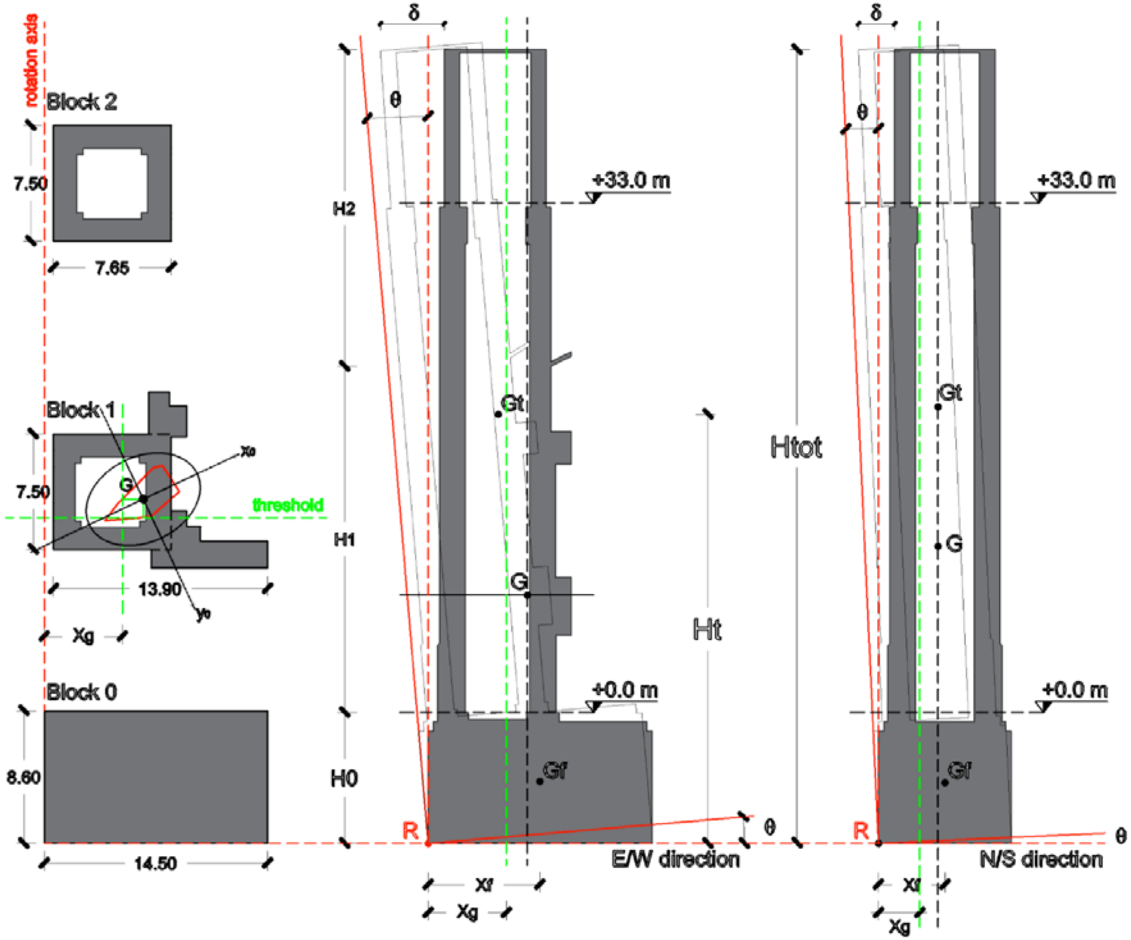
- greater oscillation amplitudes
- higher tilting values

Assumptions:

- Rigid body motion
  - → pure rotation about a fixed axis
- Equilibrium condition
  - → resultant of compressive forces within the central core of inertia
- Limit analysis
  - → no-tension material, infinite compressive strength, no sliding between units



Warning Levels and Thresholds (III)



Equilibrium Equation

$$W_{tot} \cdot x_g = W_f \cdot x_f \cos\theta + W_t \cdot h_t \cdot \sin\theta$$

infinitesimal displacements and rotations

$$(\theta << 1) \rightarrow \sin\theta \approx \theta \;\&\; \cos\theta \approx 1$$

$$W_{tot} \cdot x_g = W_f \cdot x_f + W_t \cdot h_t \cdot \theta$$

Warning Levels and Thresholds (IV)

Threshold conditions

- ❑ max tilt angle
- ❑ max top displacement

LEVEL 2

Direction	θ_{max} (°)	δ_{top} (m)
E-W	8.18	7.32
N-S	3.72	3.34

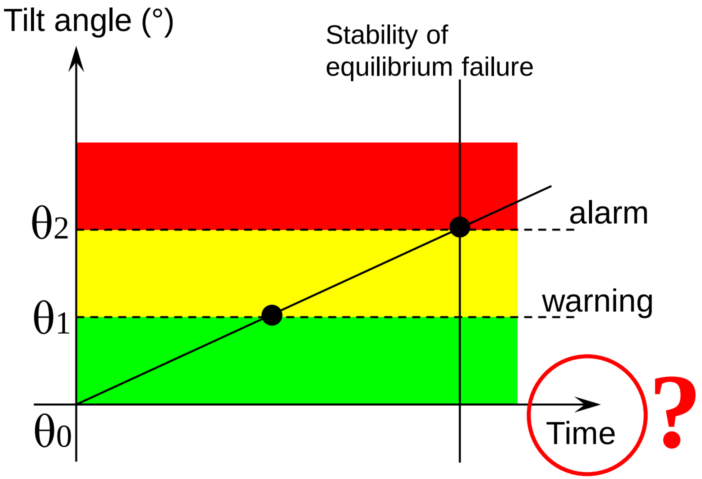
Current values*

- ❑ tilt angle
- ❑ top displacement

LEVEL 0

Direction	θ_{max} (°)	δ_{top} (m)
E-W	0.29	0.26
N-S	0.17	0.15

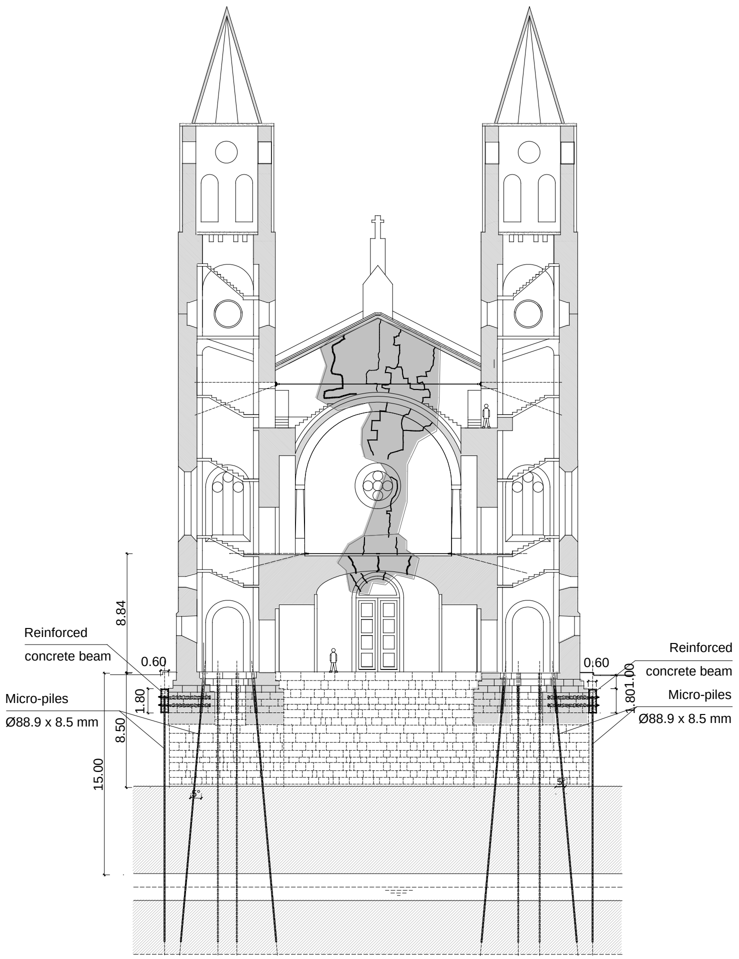
*Tilt meters + Laser scanner



- ❑ Develop predictions
- ❑ Forecast the structural response
- ❑ Estimate inspection periods
- ❑ Design of corrective measures
- ❑ Condition-based maintenance strategy

Support decision-making

Track of New KPIs after Strengthening



Strengthening Intervention

- ❑ Micro-piles alongside the towers foundation
- ❑ Post-stressed tie rods to link the towers
- ❑ Cracks injections

INSTALLATION OF A NEW MONITORING SYSTEM

Key Performance Indicators

- ❑ Crack width & opening rate
- ❑ Towers tilting
- ❑ Natural frequencies
- ❑ Mode shapes
- ❑ Correlation with ambient parameters

Final Remarks

- The assumptions adopted for the limit analysis are simplifications of the real and complex behaviour of the masonry material.
- High stress levels may cause structural failure earlier than the defined threshold conditions.
- The soil-structure interaction may deeply affect the outcome of the equilibrium analysis.

Conclusions

- The information collected via monitoring campaigns can be efficiently used and integrated within a strategy for the preservation and structural assessment of heritage buildings.
- Well-designed case-specific KPIs help control the structural integrity over time and to quantify changes in the system's response.
- The definition of threshold value conditions and warning levels is fundamental for structural management purposes.

Thank you for your attention