SHM EXPERIENCES OF MONUMENTS IN DIFFERENT STRUCTURAL, USE AND ENVIRONMENTAL CONDITIONS

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SHM: Introduction

On-site testing and monitoring can be considered key activities for a conscious knowledge-based approach in the conservation of the architectural heritage.

INVESTIGATIONS → Structural behaviour definition (ex: validation of behavioural models)

MONITORING → Permanent structural controls (continuous on site inspections)

MONITORING TECHNIQUES

STATIC MONITORING
- Measurement of static time-dependent parameters that vary slowly
- Controls of: crack pattern, activation of collapse mechanisms, state of stress and strain, variation of environmental parameters, ...
- Local controls and damage identification

DYNAMIC MONITORING
- Measurements of ambient vibrations or exceptional events (e.g. earthquakes)
- Identification of dynamic time-dependent parameters (modal parameters)
- Continuous, trigger-based or punctual
- Global controls and damage identification
Knowledge-based methodologies for the study of heritage buildings are based on the exploitation and integration of different approaches including inspections, monitoring and structural analysis.
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Prof. Ing. Claudio Modena

INTERNATIONAL WORKSHOP DISS_13
DECEMBER 12, 2013

SHM of Cultural Heritage Structures: General Knowledge-based Methodology

Role of Monitoring

- Investigation Phase
- Intervention Phase
- Evaluation Phase
- Maintenance Phase

I. Investigation
- Dynamic characterization
- Model updating
- Damage Identification
- Emergency actions

II. Execution
- Structural controls before, during and after the execution
- Incremental approach and sequential interventions

III. Evaluation
- Assessment of interventions’ influence on the structural response
  - Assessment of interventions’ effectiveness
  - Evaluation of possible upgrading solutions

Work Package 9, Knowledge based assessment, NIKER Project - EU FP7
SHM EXPERIENCES OF MONUMENTS IN DIFFERENT STRUCTURAL, USE AND ENVIRONMENTAL CONDITIONS

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**SHM of Cultural Heritage Structures: General Objectives**

**Strengthening Needs and Vulnerability Assessment**

Increase the knowledge on the structural behavior using SHM to assess strengthening needs and avoid the execution of unnecessary interventions.

**Incremental Approach/Intervention Assessment**

Application of an incremental approach to the execution of strengthening interventions using SHM before, during and after the implementation, validating eventually their effectiveness.

**Post Earthquake Controls**

Post-earthquake controls on severely damaged buildings using SHM to control the evolution of damage and verify the effectiveness of provisional strengthening measures.
## Monitoring Systems Installed and Managed by University of Padova

<table>
<thead>
<tr>
<th>Location</th>
<th>Installation Period</th>
<th>SHM Typology</th>
<th>Purpose of Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arena of Verona (VR)</td>
<td>December 2011</td>
<td>Static/Dynamic system</td>
<td>Alternative to the execution of interventions</td>
</tr>
<tr>
<td>Canzignorio Stone Tomb (VR)</td>
<td>December 2006</td>
<td>Static/Dynamic system</td>
<td>Structural controls before, during and after interventions</td>
</tr>
<tr>
<td>Scrovegni Chapel (PD)</td>
<td>October 2013</td>
<td>Static/Dynamic system</td>
<td>Vulnerability assessment / state of damage control</td>
</tr>
<tr>
<td>S. Sofia Church (PD)</td>
<td>1999 (1st installation); 2008 (1st upgrade); 2010 (2nd upgrade)</td>
<td>Static/Dynamic system</td>
<td>Structural controls before, during and after interventions</td>
</tr>
<tr>
<td>Tower of David (Jerusalem)</td>
<td>November 2013</td>
<td>Static/Dynamic system</td>
<td>Vulnerability and strengthening needs assessment / state of damage control</td>
</tr>
</tbody>
</table>
**L’Aquila Case Studies: Post-earthquake controls**

<table>
<thead>
<tr>
<th>Location</th>
<th>Installation Period</th>
<th>SHM Typology</th>
<th>Purpose of Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Civic Tower (AQ)</strong></td>
<td>July 2010</td>
<td>Static/Dynamic</td>
<td>Post-earthquake controls</td>
</tr>
<tr>
<td><strong>Spanish Fortress (AQ)</strong></td>
<td>December 2009</td>
<td>Dynamic</td>
<td>Post-earthquake controls</td>
</tr>
<tr>
<td><strong>S. Marco Church (AQ)</strong></td>
<td>August 2009</td>
<td>Static/Dynamic</td>
<td>Post-earthquake controls</td>
</tr>
<tr>
<td><strong>S. Biagio/S. Giuseppe Church (AQ)</strong></td>
<td>December 2010</td>
<td>Static/Dynamic</td>
<td>Post-earthquake controls</td>
</tr>
<tr>
<td><strong>S. Agostino Church (AQ)</strong></td>
<td>July 2010</td>
<td>Static/Dynamic</td>
<td>Post-earthquake controls</td>
</tr>
</tbody>
</table>
APPLICATION OF SHM TO SELECTED CASE STUDIES

ARENA OF VERONA: SHM AS AN ALTERNATIVE TO STRENGTHENING

GEOMETRIC AND STRUCTURAL FEATURES
- Ellipse with four focuses (152.43m x 123.23m)
- Two annular galleries and 73 radial masonry walls
- Inner masonry: multi-leaf with inner core
- ‘Wing - Ala’: freestanding structure remaining four arches of the outer ring, h=30.75 m

HISTORICAL NOTES - PAST INTERVENTIONS
- I century: construction of the amphitheater
- XII century: collapse of the outer ring
- 1939: First intervention on the ‘Wing’: buttresses construction before WWII
- 1953: Second intervention on the ‘Wing’ designed by Eng. Morandi: insertion of post-tensioned steel cables along the pillars
ARENA OF VERONA: PRELIMINARY INSPECTIONS

a. VISUAL INSPECTIONS - CRACK PATTERN SURVEY:
   - Choose the optimal position of static sensors
   - Identify principal damage and crack patterns
   - Control local cracks or entire macroelements

MAIN STRUCTURAL PROBLEMS:
   - Inner gallery’s barrel vault
   - Vaulted niches at the 1st level (‘arcovoli’)
   - Outer leaf of the perimeter stone wall
   - The ‘wing’: most vulnerable structural element
b. Operational Modal Analysis (OMA):

- Select optimal layout of dynamic system
- Identification of the dynamic behaviour of the ‘Wing’ and model updating
- Comparison of results using different OMA/EMA techniques
- SF 100 Hz; 131’072 points; record length: 21’51” sec
- System identification: decimation; segment length 2048 points, 66.67% overlap; selected methods: FDD and EFDD

<table>
<thead>
<tr>
<th>MODE</th>
<th>AVT - Oct 2011</th>
<th>FVT - 1996</th>
<th>AVT vs. FVT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FDD</td>
<td>EFDD</td>
<td>MAC</td>
</tr>
<tr>
<td>1</td>
<td>1.93</td>
<td>1.92</td>
<td>1.36</td>
</tr>
<tr>
<td>2</td>
<td>2.64</td>
<td>2.65</td>
<td>1.12</td>
</tr>
<tr>
<td>3</td>
<td>5.08</td>
<td>5.08</td>
<td>1.07</td>
</tr>
<tr>
<td>4</td>
<td>5.88</td>
<td>5.98</td>
<td>3.86</td>
</tr>
<tr>
<td>5</td>
<td>7.30</td>
<td>7.29</td>
<td>2.07</td>
</tr>
<tr>
<td>6</td>
<td>9.30</td>
<td>9.30</td>
<td>0.43</td>
</tr>
<tr>
<td>7</td>
<td>10.94</td>
<td>10.92</td>
<td>1.06</td>
</tr>
</tbody>
</table>
**ARENA OF VERONA: NEEDS OF MONITORING**

- Increase the knowledge on the structural behavior using SHM to assess strengthening needs and avoid the execution of unnecessary interventions.
- Control the structural response to different external actions, considering the relevant use/exploitation of the monument.
- SHM in the framework of a complex maintenance program of the Arena to guarantee appropriate safety conditions.
- Assessment and minimization of the seismic risk; Calibration of reference behavioural models.
- Acquisition of vibration characteristics of the monument and control of the surveyed crack pattern under operational conditions and in case of exceptional events and concerts.

**STATIC AND DYNAMIC SHM SYSTEM**
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ARENA OF VERONA: THE MONITORING SYSTEM

DYNAMIC MONITORING
16 SINGLE-AXIS ACCELEROMETERS

Sensitivity: 1019.4 mV/(m/s²)
Frequency range (± 10 %): 0.1÷2000 Hz
Resolution (at 10,000 Hz): 0.00008 m/s²
Operating temperature: -45÷82 °C

STATIC MONITORING
20 DISPLACEMENT TRANSDUCERS

Voltage: 0÷10 V
Measurement range: 10 cm
Hysteresis: < 0.01 mm
Operating temperature: -30÷100 °C

ENVIRONMENTAL MONITORING
4 TEMPERATURE/RH

Voltage: 0÷10 V
Precision: +/- 2 % RH
+/- 0.2 °C
Measurement range: 0÷100% RH - 20/0÷50 °C
ARENA OF VERONA: STATIC MONITORING RESULTS (2 YEARS)
ARENA OF VERONA - ALA: DYNAMIC MONITORING RESULTS (2 YEARS)

- Natural frequencies of the Arena’s wing are rather stable during the analysed monitoring period (Dec 2011 - Dec 2013)
- Relationship between frequencies and temperature:
  - $T > 5^\circ C \rightarrow$ frequencies are stable
  - $T < 5^\circ C \rightarrow$ frequencies tend to increase

**STATISTICAL RESULTS (FREQUENCIES - DAMPING - MAC)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_{\text{mean}}$ [Hz]</th>
<th>$f_{\text{std}}$ [Hz]</th>
<th>$\xi_{\text{mean}}$ [%]</th>
<th>$\xi_{\text{std}}$ [%]</th>
<th>$M\text{AC}_{\text{mean}}$ [%]</th>
<th>$M\text{AC}_{\text{min}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.902</td>
<td>0.051</td>
<td>0.977</td>
<td>0.359</td>
<td>90.66</td>
<td>70.30</td>
</tr>
<tr>
<td>2</td>
<td>2.621</td>
<td>0.097</td>
<td>0.903</td>
<td>0.326</td>
<td>89.10</td>
<td>70.55</td>
</tr>
<tr>
<td>3</td>
<td>4.888</td>
<td>0.240</td>
<td>1.037</td>
<td>0.226</td>
<td>94.15</td>
<td>70.98</td>
</tr>
<tr>
<td>4</td>
<td>6.016</td>
<td>0.232</td>
<td>5.247</td>
<td>1.527</td>
<td>96.62</td>
<td>74.25</td>
</tr>
<tr>
<td>5</td>
<td>7.091</td>
<td>0.253</td>
<td>1.933</td>
<td>0.772</td>
<td>94.25</td>
<td>70.11</td>
</tr>
<tr>
<td>6</td>
<td>9.028</td>
<td>0.575</td>
<td>0.961</td>
<td>0.365</td>
<td>86.93</td>
<td>70.01</td>
</tr>
<tr>
<td>7</td>
<td>10.555</td>
<td>0.384</td>
<td>1.119</td>
<td>0.229</td>
<td>94.91</td>
<td>70.03</td>
</tr>
</tbody>
</table>
**ARENA OF VERONA: MODEL DRIVEN APPROACH**

- Model driven approach → exploit SHM and dynamic identification results to calibrate and validate reference numerical models
- Implementation of modal matching procedures
- Model updating targets: material properties, geometry, morphology, connections, boundary conditions, soil-structure interaction, damage distribution, etc.

**FE MODEL OF THE ARENA’S WING**

**CALIBRATION PROCEDURE**

- Identification of morphology and materials
- Definition of initial values of elastic mechanical properties
- Iterative variation of mechanical properties/boundary conditions within a predefined range until reaching the final calibration
**ARENA OF VERONA: MODEL UPDATING RESULTS**

**MODE MATCHING: EXP/FEM RESULTS**

<table>
<thead>
<tr>
<th>MODE</th>
<th>Type</th>
<th>(f_{\text{EXP}}) [Hz]</th>
<th>(f_{\text{FEM}}) [Hz]</th>
<th>Average error (\epsilon) [%]</th>
<th>MAC ([\langle \psi_{\text{EXP}}, \psi_{\text{FEM}} \rangle \rangle])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1(^{st}) out-of-plane bend.</td>
<td>1.924</td>
<td>1.924</td>
<td>0.01</td>
<td>0.973</td>
</tr>
<tr>
<td>2</td>
<td>1(^{st}) torsional</td>
<td>2.666</td>
<td>2.640</td>
<td>1.00</td>
<td>0.993</td>
</tr>
<tr>
<td>3</td>
<td>2(^{nd}) torsional</td>
<td>5.103</td>
<td>5.122</td>
<td>0.36</td>
<td>0.984</td>
</tr>
<tr>
<td>4</td>
<td>2(^{nd}) out-of-plane bend.</td>
<td>6.086</td>
<td>6.054</td>
<td>0.53</td>
<td>0.936</td>
</tr>
<tr>
<td>5</td>
<td>3(^{rd}) torsional</td>
<td>7.308</td>
<td>7.323</td>
<td>0.20</td>
<td>0.886</td>
</tr>
<tr>
<td>6</td>
<td>4(^{th}) torsional</td>
<td>9.434</td>
<td>9.464</td>
<td>0.32</td>
<td>0.821</td>
</tr>
<tr>
<td>7</td>
<td>5(^{th}) torsional</td>
<td>10.970</td>
<td>10.944</td>
<td>0.24</td>
<td>0.973</td>
</tr>
</tbody>
</table>

**VARIATION OF UPDATING PARAMETERS**

<table>
<thead>
<tr>
<th>Structural element</th>
<th>ELASTIC MODULUS [MPa]</th>
<th>MASS DENSITY [kg/m(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>Stone I order</td>
<td>15000</td>
<td>15223</td>
</tr>
<tr>
<td>Stone II order</td>
<td>15000</td>
<td>16174</td>
</tr>
<tr>
<td>Stone III order</td>
<td>15000</td>
<td>14443</td>
</tr>
<tr>
<td>Vault</td>
<td>2400</td>
<td>2479</td>
</tr>
<tr>
<td>Arches</td>
<td>15000</td>
<td>14056</td>
</tr>
<tr>
<td>Fresneli</td>
<td>500</td>
<td>477</td>
</tr>
<tr>
<td>Infill</td>
<td>500</td>
<td>483</td>
</tr>
<tr>
<td>Stone floor</td>
<td>12000</td>
<td>11723</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL MODE SHAPES**

- MODE 1 - 1.92 Hz
- MODE 2 - 2.64 Hz
- MODE 3 - 5.88 Hz
- MODE 4 - 5.88 Hz
- MODE 5 - 7.30 Hz
- MODE 6 - 9.30 Hz
- MODE 7 - 10.94 Hz

**NUMERICAL MODE SHAPES**

- Mode 1 (1.924 Hz)
- Mode 2 (2.640 Hz)
- Mode 3 (5.122 Hz)
- Mode 4 (6.054 Hz)
- Mode 5 (6.728 Hz)
- Mode 6 (7.323 Hz)
- Mode 7 (10.944 Hz)

* In-plane bending mode not identified during AVT and dynamic monitoring.
5 Main seismic events (with several aftershocks) recorded from January to May 2012:

1. Prealpi Venete
2. Reggio Emilia province
3. Parma province
4. Emilia-Romagna: Finale Emilia
5. Emilia-Romagna: Medolla
ANALYSIS OF GROUND MOTION RECORDS

MAIN SHOCK: 25 JANUARY 2012
Prealpi Venete (VR) 2012-01-24 23:54:46
Magnitude: 4.2
Depth: 10.3 Km
Distance: 11.5 Km
Max. Acc. Base = 0.62 m/s²
Max Acc. Wing = 1.93 m/s²
Amplif. factor = 3.11

MAIN SHOCK: 29 MAY 2012
Pianura Padana-Emiliana (MO) 2012-05-29 07:00:03
Magnitude: 5.8
Depth: 10.2 Km
Distance: 75 Km
Max. Acc. Base = 0.08 m/s²
Max Acc. Wing = 0.98 m/s²
Amplif. factor = 12.56

COMPARISON: MAX. ACCELERATIONS, AMPLIFICATION FACTORS AND ELASTIC RESPONSE SPECTRA

<table>
<thead>
<tr>
<th>Seismic event</th>
<th>BASE</th>
<th>TOP WING</th>
<th>TOP AMPHITHEATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>25/01/2012</td>
<td>0.619</td>
<td>1.93</td>
<td>3.11</td>
</tr>
<tr>
<td>29/05/2012</td>
<td>0.078</td>
<td>0.98</td>
<td>12.56</td>
</tr>
</tbody>
</table>
**Modal parameters identification**

**Main shock: 25 January 2012**

- Dynamic identification of modal parameters before, during and after the seismic event
- Input is not a white noise stochastic process
- Earthquake is a nonstationary signal
- Frequency spectrum of the transient input biases modal parameter estimation
- OMA techniques not reliable

**Natural frequencies variation**

**Modal damping variation**

**Datos-driven reference-based deterministic-stochastic subspace identification (CSI/REF) method**
NUMERICAL SIMULATION

- FE simulation on the main shock of the 25/01/2012 earthquake
- Type of analysis: linear and non-linear dynamic
- Aims:
  a) Compare the actual response (experimentally recorded) with the model response (numerically predicted)
  b) Refine the calibration of the reference FE model: modification of the elastic properties and of the damping coefficients, accurately estimated during a real earthquake

NON-LINEAR CONSTITUTIVE MODEL OF MASONRY

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength $f_t$ [MPa]</th>
<th>Fracture energy $G_f$ [N/mm]</th>
<th>Compressive strength $f_c$ [MPa]</th>
<th>Elastic Hardening $E_{hcr}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone blocks masonry</td>
<td>0.13</td>
<td>-</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Opus caementicum (vaults and arches)</td>
<td>0.13</td>
<td>-</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Infill of vaults</td>
<td>linear elastic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone floor</td>
<td>linear elastic</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DAMPING COEFFICIENT CALIBRATION

From dynamic identification during the earthquake

<table>
<thead>
<tr>
<th>MODE</th>
<th>BE [%]</th>
<th>MS [%]</th>
<th>PP [%]</th>
<th>AE [%]</th>
<th>$\xi$ change (BE-MS)</th>
<th>$\xi$ change (BE-AE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.17</td>
<td>2.71</td>
<td>2.18</td>
<td>0.96</td>
<td>+131.47%</td>
<td>-22.25%</td>
</tr>
<tr>
<td>2</td>
<td>1.11</td>
<td>5.11</td>
<td>2.67</td>
<td>0.82</td>
<td>+361.43%</td>
<td>-35.21%</td>
</tr>
<tr>
<td>3</td>
<td>1.03</td>
<td>n.i.*</td>
<td>1.30</td>
<td>0.96</td>
<td>/</td>
<td>-7.10%</td>
</tr>
<tr>
<td>4</td>
<td>6.44</td>
<td>1.97</td>
<td>3.75</td>
<td>4.87</td>
<td>-69.45%</td>
<td>-32.23%</td>
</tr>
<tr>
<td>5</td>
<td>2.81</td>
<td>6.64</td>
<td>4.38</td>
<td>2.30</td>
<td>+136.19%</td>
<td>-22.44%</td>
</tr>
<tr>
<td>6</td>
<td>0.95</td>
<td>n.i.*</td>
<td>n.i.*</td>
<td>0.99</td>
<td>/</td>
<td>+3.71%</td>
</tr>
<tr>
<td>7</td>
<td>1.34</td>
<td>3.57</td>
<td>1.93</td>
<td>1.19</td>
<td>+166.63%</td>
<td>-12.51%</td>
</tr>
</tbody>
</table>

Reyleigh damping: $C = aM + bK$

a, b Reyleigh coefficients calculated on the estimated damping ratio $\xi$
**NUMERICAL SIMULATION**

**Table:**

<table>
<thead>
<tr>
<th>Model</th>
<th>III order</th>
<th>II order</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Acc. 1 [m/s²]</td>
<td>Max Acc. 3 [m/s²]</td>
</tr>
<tr>
<td>Experimental</td>
<td>1,934</td>
<td>1,840</td>
</tr>
<tr>
<td>FE linear</td>
<td>2,253</td>
<td>2,06</td>
</tr>
<tr>
<td>FE non linear</td>
<td>1,702</td>
<td>1,86</td>
</tr>
</tbody>
</table>

**Fit index comparison EXP/FEM**

\[
fit = 100 \frac{1 - \text{norm}(y_{fem} - y_{exp})}{\text{norm}(y_{exp} - \bar{y}_{exp})}
\]
NUMERICAL SIMULATION
The Scrovegni Chapel, dedicated to St. Mary of the Charity, frescoed between 1303 and 1305 by Giotto, is one of the most important masterpieces of Italy. The frescoes, which narrate events on the lives of the Virgin Mary and Christ, cover the entire walls.

**XX C. STRENGTHENING INTERVENTIONS**
- 1957 → Strengthening interventions of the façade through the insertion of 3 horizontal ties;
- 1961-63 → Substitution of the old steel ties;
- 1961-63 → Substitution of the wooden trusses of the roof;
- 2006-08: important consolidation interventions
**Scrovesegni Chapel: Preliminary Inspections**

**Crack Pattern Survey**

**Dynamic Tests on Steel Ties**
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INTERNATIONAL WORKSHOP DISS_13
DECEMBER 12, 2013

DYNAMIC IDENTIFICATION TESTS

FLAT JACK TESTS
CORING ON MASONRY WALLS
GEOTECHNICAL CORING
Scrovegni Chapel: Monitoring Systems

Monitoring System 1997-1998 → Crack Pattern Controls

Monitoring System May-July 2011 → Crack Pattern Controls
PERMANENT STRUCTURAL HEALTH MONITORING SYSTEM (INSTALLED OCT. 2013)

**Dynamic Monitoring**
- 8 Single-axis accelerometers

**Static Monitoring**
- 8 Displacement transducers
- 2 Inclinometers

**Environmental Monitoring**
- 2 Temperature/Relative humidity sensors
CRACK OPENING (OCT-DEC 2013)

PZ1, PZ4, PZ7

PZ2, PZ3, PZ6

PZ5, PZ8

LONG. WALLS HORIZ. DISPLACEMENT (OCT-DEC 2013)  OUT-OF-PLANE

I1, I2

PZ01, PZ04, PZ07  TINT  TExt

PZ02, PZ03, PZ06  TINT  TExt

IN01, IN02

MINISTRY OF FINANCE

MINISTRY OF INFRASTRUTTURE
HISTORICAL NOTES

- The Roman Bridge of S. Lorenzo is the best preserved and most famous Paduan bridge remaining from Roman times.
- The bridge has been restored several times over centuries.
- In 1938 an archaeological excavation was undertaken, in consequence of the laying of the foundations for the new wing of the University (the Bò).
- In 1959 the first arch of the bridge was partially buried as a result of the filling of the Canal.

GEOMETRIC AND MATERIAL FEATURES

- The bridge was about 53.30 metres (180 Roman feet) long, 44 metres without the access road, and 8.35 metres wide, while the roadway was 7.40 metres (about 25 Roman feet) wide.
- The need to facilitate the passage of the boats help to explain the exceptional structure of the bridge, including the high, narrow piers and unusually flat arches.
- The bridge has three arches using blocks of trachite from the Euganean Hills and armille and limestone from Costozza.
**Dynamic Monitoring System Layout**

MONITORING STRATEGY

- Analysis of traffic-induced vibrations
- 10 day of continuous dynamic monitoring
- 18 single-axis accelerometers
- 1 basis (3 sensors in x,y,z directions) at the pile’s basement
- 3 basis (3 sensors x,y,z) in the 1st span at different heights
- 1 basis (3 sensors x,y,z) in the 2nd and 3rd span at arch’s top
**VISUAL MONITORING - VEHICULAR TRAFFIC ANALYSIS**

**SIGNAL PROCESSING**

- Acceleration measurement - sampling frequency 100 Hz
- High-pass filtering of the signals - cutoff frequency 1 Hz
- Numerical integration of the signal to convert accelerations into velocities
- Successive High-pass filtering of the signals - cutoff frequency 1 Hz

**TIME HISTORY OF THE VELOCITIES - VERTICAL DIRECTION - IDENTIFICATION OF THE TYPE OF VEHICLES**

[Graphs showing time history of velocities in longitudinal and transversal directions]
REFERENCE VALUES OF THE PEAK COMPONENT
PARTICLE VELOCITY (DIN 4150)

<table>
<thead>
<tr>
<th>Classe</th>
<th>Tipo di edificio</th>
<th>Valori di riferimento per la velocità di vibrazione ppv in mm/s (per tutte le frequenze)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Costruzioni industriali, edifici industriali e costruzioni strutturalmente simili</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Edifici residenziali e costruzioni simili</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Costruzioni che non ricadono nelle classi 1 e 2 e che sono degne di essere tutelate (per esempio monumenti storici)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

REFERENCE VALUES OF THE PEAK COMPONENT
PARTICLE VELOCITY (SN 640312)

<table>
<thead>
<tr>
<th>Classe</th>
<th>Tipo di costruzione</th>
<th>Esposizione</th>
<th>Valori di riferimento per la velocità di vibrazione ppv in mm/s</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Da 8 Hz fino a 30 Hz</td>
<td>Da 30 Hz fino a 60 Hz</td>
</tr>
<tr>
<td>A</td>
<td>Costruzioni molto poco sensibili (per esempio ponti, gallerie, fondazioni di macchine)</td>
<td>Occasionale Frequente</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Permanente</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>Costruzioni poco sensibili (per esempio edifici industriali in cemento armato o metallici) costruiti a regola d'arte e con manutenzione adeguata</td>
<td>Occasionale</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frequente</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>Costruzioni normalmente sensibili (per esempio edifici d'abitazione in muratura di cemento, cemento armato o mattoni, edifici amministrativi, scuole, ospedali, chiese in pietra naturale o mattoni intonacati) costruiti a regola d'arte e con manutenzione adeguata</td>
<td>Occasionale</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frequente</td>
<td>20</td>
</tr>
<tr>
<td>D</td>
<td>Costruzioni particolarmente sensibili (per esempio monumenti storici e soggetti a tutela) case con soffitti in gesso, edifici della classe C nuovi o ri-</td>
<td>Occasionale Previsioni</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frequente</td>
<td>20</td>
</tr>
</tbody>
</table>

*) Le posizioni di misura devono essere scelte sugli elementi rigidi della struttura portante o dove sono attesi i maggiori effetti delle vibrazioni.

HISTORIC BUILDINGS & MONUMENTS
2.5 mm/s

- PERMANENT VIBRATIONS
- POSSIBLE FATIGUE PHENOMENA
- VALUES FOR ALL THE FREQUENCY SPECTRUM

DELICATE BUILDINGS SUCH AS CH
BUILDINGS & MONUMENTS
1.5 - 3.0 mm/s
Traffic-induced vibrations are generally not of high intensity:

- Bus passage causes in some traffic conditions, vibrations intensity above the threshold (maximum 3.43 mm/sec).
- Tram passage generally induces less vibrations amplitude (up to 1.41 mm/sec).
ANALYSIS OF TRAFFIC-INDUCED VIBRATIONS

DISTRIBUTION OF TRAFFIC INTENSITY LEVEL DURING 24 HOURS (00:00 - 24:00)
LIGHT VEHICLES → BLUE
HEAVY VEHICLES → RED

ANALYSIS OF RECORDED VELOCITIES OVER THE ENTIRE PERIOD (10 DAYS)

- 3% OF VEHICLES EXCEED THE DIN 4150 THRESHOLD (2.5 MM/S)
- 12% OF VEHICLES EXCEED THE SN 640312 RANGE (1.5 - 3.0 MM/S)

DISTRIBUTION OF TRAFFIC INTENSITY LEVEL DURING 10 DAY OF CONTINUOUS MONITORING

SUNDAY
CANSIGNORIO STONE TOMB: SHM TO VALIDATE THE EFFECTIVENESS OF INTERVENTIONS

GEOMETRIC AND MATERIAL FEATURES
- Placed in the monumental area of S. Maria Antica;
- Funerary monument of ‘Scaligeri’ family, in the Gothic style;
- Hexagonal plan, full of sculptures, spired tabernacles and decorations; equestrian sculpture on the top
- Soft limestone (gallina), red Verona marble, marble of Candoglia.

HISTORICAL NOTES - PAST INTERVENTIONS
- 1374-1376: Construction following the drawings of Bonino da Campione;
- from 1676: periodical restoration works;
- 1915-19, 1940-45: anti-aircraft protections;
- 2006-08: important consolidation interventions
CANSIGNORIO STONE TOMB: STRENGTHENING INTERVENTION (2006-2008)

LOCAL AND GLOBAL INTERVENTIONS
CANSIGNORIO STONE TOMB: PRELIMINARY INSPECTIONS

a. Operational Modal Analysis (OMA):

- Definition of the optimal layout of the dynamic system
- Identification of the dynamic behaviour of the monument
- Model updating
- SF 100 Hz; 131'072 points; record length: 21’51” sec
- System identification: decimation; segment length 2048 points, 66.67% overlap; selected method: FDD

<table>
<thead>
<tr>
<th>MODE</th>
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<th>Comment</th>
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<tbody>
<tr>
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<td>3</td>
<td>5.91</td>
<td>1st torsional</td>
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<tr>
<td>4</td>
<td>12.60</td>
<td>2nd bending NS</td>
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<td>5</td>
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<td>2nd bending EO</td>
</tr>
<tr>
<td>6</td>
<td>19.43</td>
<td>2nd torsional</td>
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</tbody>
</table>

SETUP 1  SETUP 2  SETUP 3
**Cansignorio Stone Tomb: The Monitoring System**

**Needs of Monitoring:**

- Application of SHM before, during and after interventions’ execution
- Evaluate on-site the effectiveness of performed strengthening interventions
- Assessment of possible upgrading solutions
- Application of an incremental approach to interventions

**Dynamic Monitoring**

4 Single-axis accelerometers

- Sensitivity: 1019.4 mV/(m/s²)
- Frequency range (± 10%): 0.1÷2000 Hz
- Resolution (at 10,000 Hz): 0.00008 m/s²
- Operating temperature: -45÷82 °C

**Static Monitoring**

2 Displacement transducers

- Voltage: 0÷10 V
- Measurement range: 10 cm
- Hysteresis: < 0.01 mm
- Operating temperature: -30÷100 °C

**Environmental Monitoring**

1 Temperature/RH

- Voltage: 0÷10 V
- Precision: +/- 2 % RH
- +/- 0.2 °C
- Measurement range: 0÷100% RH
- -20/0÷50 °C
CANSIGNORIO STONE TOMB: NATURAL FREQUENCIES VARIATION (7 YEARS)
Cansignorio Stone Tomb: Cracks Opening (7 Years)

PZ 01: Presence of an active deterioration/damaging process

PZ 02: Reversible deformations of the crack strictly related to seasonal thermal cycles. No active damage
L’Aquila case studies: SHM for post-earthquake controls

**Needs of monitoring:**

- Evaluate quantitatively the progression of the damage pattern
- Design effective and urgent provisional interventions to prevent further collapses
- Define an early warning procedure for the safety of the workers employed in the strengthening interventions
- Schedule the execution of definitive interventions (heavy reconstructions)
The Spanish Fortress is located in the north-east part of the city of l’Aquila. It is one of the most impressive Renaissance castles in Central and Southern Italy.

**GEOMETRIC AND MATERIAL FEATURES**

- Composed by 4 bastions connected through massive defensive walls (60 m long, 20m tick at the base and 5m thick at the top)
- Surrounded by a deep ditch 23 m wide, 14 m deep
- Perimeter walls: irregular stone masonry with external covering made of travertine

**HISTORICAL NOTES - PAST INTERVENTIONS**

- XV sec.: l’Aquila is the second most powerful city of the Naples’ Kingdom, under Spanish domination
- 1534: beginning of the fortress’ construction, designed by a Spanish architect
- 1949-1951: restoration works; the fortress became the seat of the National Museum of Abruzzi
SPANISH FORTRESS: 6 APRIL 2009 EARTHQUAKE

EARTHQUAKE-INDUCED DAMAGES:
- Out of plane overturning of the longitudinal walls
- Collapse of the main façade’s and of the roof
- Shear damages and collapses in the inner walls
- Damage to arches, local collapse of vaults and floors
- Overturning mechanisms of the pillars

PROVISIONAL INTERVENTIONS:
- Structural stability provided by relying on the remaining strength of the resisting elements, i.e. connecting the internal and external façades of the damages wings by means of stainless steel cables, to avoid overturning mechanisms.
- Reconstruction of the roof, using steel trusses and a light covering structure made of wood.
SPANISH FORTRESS: PRELIMINARY INSPECTIONS

a. OPERATIONAL MODAL ANALYSIS (OMA):

- Execution of AVT on the SE wing of the fortress
- Identification of the dynamic response in the damaged state: assess if the structure has still a unitary dynamic behaviour
- Definition of the optimal layout of the dynamic monitoring system
- Model updating
- SF 100 Hz; 131’072 points; record length: 21’51” sec
- SI: decimation; selected OMA techniques: FDD and EFDD
**Spanish Fortress: The Monitoring System**

The dynamic monitoring system is composed by an acquisition unit connected to eight high sensitivity piezoelectric accelerometers. The central unit, located at the second floor of the fortress, in the South-East wing, is provided with a Wi-Fi router for remote data transmission. A couple of reference sensors is fixed at the base of the structure for the record of the ground acceleration both in operational conditions and during seismic events.

**Dynamic Monitoring**

8 single-axis accelerometers

**Monitoring Strategy:** Trigger-based
Spanish Fortress: Natural Frequencies Variation (3 years)
**SHM: Structural Assessment and Damage Detection**

- Definition of clear procedures to interpret, post-process and exploit SHM results

**DATA DRIVEN APPROACH**

- Creation of a statistical model of the system

**MODEL DRIVEN APPROACH**

- Creation of a high-fidelity physical model of the structure

**DATA DRIVEN APPROACH: Modelling Environmental Effects through Black Box Models**

- Aim: Filter out environmental effects from recorded data and extracted features: decompose the measurements into their reversible and irreversible component and provide object criteria for damage detection

- Application of regression analysis to establish relationships between observed environmental factors (inputs) and estimated natural frequencies (outputs)

- Implementation of dynamic models → ARX models (Auto-Regressive output with an eXogenous input) (Ljung 1999)
**Modelling Environmental Effects through Black Box Models**

### Description of the Procedure:

**Correlation Analysis**
- Selection of ARX model predictors

**Data Normalization**
- Means removal from inputs and outputs

**ARX Models Construction**
- Estimation of ARX SISO models and their statistical properties

**Best Model Selection**
- Quality criteria (Ljung 1999)

**Response Prediction**
- Simulation of the response based on new environmental data

**Residual Analysis**
- Calculation of simulation error and its statistics

**Confidence Intervals**
- Calculation of 95% CI using a statistical table of the T-student distribution

**Damage Detection**
- CI as an object criterion for damage detection (outliers analysis)

\[
\hat{r}_{xy} = \frac{\text{cov}(x_k, y_k)}{\sigma_x \sigma_y} \quad \text{estimated covariance}
\]

\[
\bar{x}_k, \bar{y}_k = \frac{x_k^m - \bar{x}_k}{\sigma_x}, \quad \frac{y_k^m - \bar{y}_k}{\sigma_y} \quad \text{estimated standard deviation}
\]

\[
\text{ARX } [n_a, n_b, n_k] = [1:10, 1:10, 1:10]
\]

Loss Function; Akaike’s Final Prediction Error FPE; Coefficient of determination; Autocorrelation functions of residuals

\[
e_k = y_k - \hat{y}_k \quad \text{and} \quad \hat{\sigma}_y
\]

\[
[y - t_{a/2, v} \hat{\sigma}_y, \quad \hat{y} - t_{a/2, v} \hat{\sigma}_y]
\]
**SPANISH FORTRESS: DAMAGE DETECTION**

- Monitoring period: 22/12/2009 - 22/01/2013 → 3 years
- Construction of ARX models on the first 4 natural frequencies

**STATISTICAL RESULTS OF MONITORING**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( f_{\text{MAX}} ) [Hz]</th>
<th>( f_{\text{MIN}} ) [Hz]</th>
<th>( f_{\text{RECM}} ) [Hz]</th>
<th>( f_{\text{VAR}} ) [%]</th>
<th>( f_{\text{STD}} ) [Hz]</th>
<th>( f_{\text{CV}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.213</td>
<td>2.819</td>
<td>2.962</td>
<td>13.98</td>
<td>0.097</td>
<td>3.26</td>
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<tr>
<td>2</td>
<td>4.675</td>
<td>3.876</td>
<td>4.274</td>
<td>20.60</td>
<td>0.172</td>
<td>4.02</td>
</tr>
<tr>
<td>3</td>
<td>5.963</td>
<td>4.885</td>
<td>5.457</td>
<td>19.63</td>
<td>0.278</td>
<td>5.10</td>
</tr>
<tr>
<td>4</td>
<td>6.201</td>
<td>5.542</td>
<td>5.872</td>
<td>11.91</td>
<td>0.153</td>
<td>2.61</td>
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<td>5</td>
<td>9.688</td>
<td>7.069</td>
<td>8.968</td>
<td>35.77</td>
<td>0.505</td>
<td>5.80</td>
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</tbody>
</table>

**CORRELATION ANALYSIS**

<table>
<thead>
<tr>
<th>CORRELATION COEFFICIENTS</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( f_3 )</th>
<th>( f_4 )</th>
<th>( f_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 )</td>
<td>0.86</td>
<td>0.79</td>
<td>0.61</td>
<td>0.63</td>
<td>0.40</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>0.89</td>
<td>0.79</td>
<td>0.61</td>
<td>0.63</td>
<td>0.40</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>0.88</td>
<td>0.79</td>
<td>0.60</td>
<td>0.63</td>
<td>0.40</td>
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<tr>
<td>( T_4 )</td>
<td>0.89</td>
<td>0.79</td>
<td>0.60</td>
<td>0.62</td>
<td>0.40</td>
</tr>
<tr>
<td>( T_5 )</td>
<td>0.86</td>
<td>0.78</td>
<td>0.61</td>
<td>0.63</td>
<td>0.40</td>
</tr>
<tr>
<td>( T_6 )</td>
<td>0.90</td>
<td>0.81</td>
<td>0.64</td>
<td>0.66</td>
<td>0.41</td>
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<tr>
<td>( T_7 )</td>
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<td>0.80</td>
<td>0.64</td>
<td>0.66</td>
<td>0.41</td>
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**ARX MODELS SELECTION BASED ON QUALITY CRITERIA**

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<thead>
<tr>
<th>Mode</th>
<th>( n_0 )</th>
<th>( n_1 )</th>
<th>( n_2 )</th>
<th>( \lambda_0 )</th>
<th>( FPE )</th>
<th>( R^2 )</th>
<th>( n_0 )</th>
<th>( n_1 )</th>
<th>( n_2 )</th>
<th>( \lambda_0 )</th>
<th>( FPE )</th>
<th>( R^2 )</th>
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<td>7</td>
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<td>0.0004</td>
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</tr>
<tr>
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<td>0.0166</td>
<td>0.43</td>
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</tbody>
</table>
Conclusions

- Natural frequencies of the first 4 structural modes are generally included within confidence intervals.
- The damage pattern induced by the earthquake is stable during the validation period (last 2 years of SHM).
- Provisional strengthening interventions are effective and prevented further damages/collapses.
The Civic Tower is located in the heart of the historical city center of l’Aquila and it’s part of the complex of the l’Aquila City Hall composed by two bodies: the Margherita Palace and the Tower.

**GEOMETRIC AND MATERIAL FEATURES**
- 6,27m long, 6,42m wide, 42m high
- Covering: calcareous stone blocks
- Presence of some orders of bricks at the second level
- Presence of ancient tiles

**HISTORICAL NOTES - PAST INTERVENTIONS**
- XIII sec.: first construction of the tower, originally conceived as an isolated element
- 1294: construction of ‘Margherita’ palace
- 1349, 1461 and 1703: strong earthquakes induced several damages/collapses
Civic Tower: 6 April 2009 Earthquake

Earthquake-induced damages:
- West façade: vertical cracks
- East and South façades: cracks at the bottom of the tower due to stress concentrations
- South façade: failure of an existing tie
- Detachment of the tower from the Palace

Provisional Interventions:
- Confinement system of the tower (steel beams, ties and timber frames)
- Improvement of the tower-palace connection
- Propping system of the palace’s perimeter walls to prevent out-of-plane overturning
**Civic Tower: Preliminary Inspections**

### a. Operational Modal Analysis (OMA):

- Definition of the optimal layout of the dynamic system
- Identification of the dynamic behaviour in the damaged state
- Model updating
- SF 80 Hz; 144’000 points; record length: 30’
- SI: decimation; selected OMA techniques: FDD, EFDD, pLSCF

<table>
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<tr>
<th>MODE</th>
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<th>EFDD [Hz]</th>
<th>MAC</th>
<th>Comment</th>
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<td>1,583</td>
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<td>1st bend. NS</td>
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<tr>
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<td>3,301</td>
<td>3,292</td>
<td>0,89</td>
<td>2nd bend. NS</td>
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<td>3,699</td>
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<td>0,76</td>
<td>3rd bend. EO</td>
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</table>

<table>
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<td>6,419</td>
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</table>
Civic Tower: The Monitoring System

**Static System**
- Displacement transducer
- Thermo couples
- Strain gauges
- Inclinometer

**Dynamic System**
- 8 single-axis accelerometers

**Dynamic Monitoring**
- 5 displacement transducers
- 6 strain gauges
- 1 inclinometer

**Environmental Monitoring**
- 6 thermo couples
CIVIC TOWER: Static monitoring results

During the first 1,5 years of monitoring the crack pattern of the tower was kept rather stable.

Starting from February 2012 the equilibrium conditions of the tower underwent a significant change due to a slight rotation/displacement of the tower toward the palace.
CIVIC TOWER: DAMAGE DETECTION

- Monitoring period: 22/07/2010 - 09/01/2013 → 2,5 years
- Construction of ARX models on the first 5 natural frequencies

**Statistical results of monitoring**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_{\text{max}}$ [Hz]</th>
<th>$f_{\text{min}}$ [Hz]</th>
<th>$f_{\text{mean}}$ [Hz]</th>
<th>$f_{\text{range}}$ [%]</th>
<th>$f_{\text{stat}}$ [Hz]</th>
<th>$f_{\text{cor}}$ [%]</th>
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<tbody>
<tr>
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<td>1.701</td>
<td>1.533</td>
<td>1.604</td>
<td>10.92</td>
<td>0.047</td>
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<td>2</td>
<td>1.752</td>
<td>1.531</td>
<td>1.642</td>
<td>14.44</td>
<td>0.060</td>
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<tr>
<td>3</td>
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<td>2.988</td>
<td>3.150</td>
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<td>5.786</td>
<td>6.305</td>
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</table>

**Correlation analysis**

<table>
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<tr>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
<th>$f_4$</th>
<th>$f_5$</th>
<th>$f_6$</th>
<th>$f_7$</th>
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<tbody>
<tr>
<td>$T_1$</td>
<td>0.23</td>
<td>0.20</td>
<td>0.50</td>
<td>0.84</td>
<td>0.41</td>
<td>0.13</td>
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<tr>
<td>$T_2$</td>
<td>0.15</td>
<td>0.27</td>
<td>0.49</td>
<td>0.81</td>
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<tr>
<td>$T_3$</td>
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<td>0.35</td>
<td>0.44</td>
<td>0.76</td>
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<tr>
<td>$T_4$</td>
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<td>0.35</td>
<td>0.44</td>
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<td>$T_5$</td>
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<td>0.36</td>
<td>0.43</td>
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<tr>
<td>$T_6$</td>
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<td>0.46</td>
<td>0.78</td>
<td>0.53</td>
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</table>

**ARX models selection based on quality criteria**

<table>
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<tr>
<th>Mode</th>
<th>$n_a$</th>
<th>$n_b$</th>
<th>$n_c$</th>
<th>$\lambda_0$</th>
<th>FPE</th>
<th>$R^2$</th>
<th>$n_a$</th>
<th>$n_b$</th>
<th>$n_c$</th>
<th>$\lambda_0$</th>
<th>FPE</th>
<th>$R^2$</th>
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<td>0.0004</td>
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<td>0.0055</td>
<td>0.0056</td>
<td>0.55</td>
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</table>
**CONCLUSIONS**

- Until Feb 2012 → damage is stable since the residuals are always included within confidence intervals
- From Feb 2012 → the equilibrium condition of the tower changed due to a displacement of the tower
- It was possible to detect damage/modification of the structural layout demonstrated by an increment of frequencies
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THANK YOU FOR YOUR KIND ATTENTION

SHM EXPERIENCES OF MONUMENTS IN DIFFERENT STRUCTURAL, USE AND ENVIRONMENTAL CONDITIONS

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ORDINARIO DI TECNICA DELLE COSTRUZIONI

UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA CIVILE, EDILE E AMBIENTALE