Seismic Risk Preparedness and Mitigation of Culture Heritage Sites
מוכנות והיערכות לסיכוני רעידות אדמה באתרי מורשת תרבות
Israel, Jerusalem. 19-20 January 2014 ירושלים. יח'-יט' בשבט, תשע"ד

INVESTIGATION TECHNIQUES - MONITORING: THE CASE OF THE DAVID TOWER

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ICEA
INGEGNERIA CIVILE, EDILE E AMBIENTALE
CIVIL, ARCHITECTURAL AND ENVIRONMENTAL ENGINEERING

SHM: INTRODUCTION

- Needs for an effective seismic protection and vulnerability reduction of infrastructures, strategic structures and Cultural Heritage (CH) buildings;
- Cultural Heritage buildings are constantly at risk, as demonstrated by recent earthquakes;
- Historic buildings, due to their structural features, construction techniques and used materials, are particularly vulnerable to earthquake actions;

STRUCTURAL HEALTH MONITORING (SHM)

a measure of passive mitigation of earthquake effects

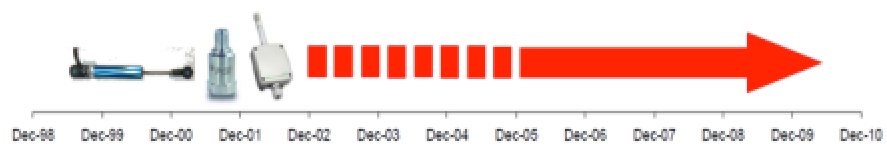
- Continuous or short/medium-term controls of quantities related to the structural behavior and connected to the evaluation of their evolution with the passing of time;
- Large number of applications in the field of civil engineering such as: design, damage detection and assessment, maintenance and retrofitting of existing structures, structural control during earthquakes (using semi-active systems).

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 → Permenent structural controls (continuous on site inspections)



MONITORING TECHNIQUES

STATIC MONITORING

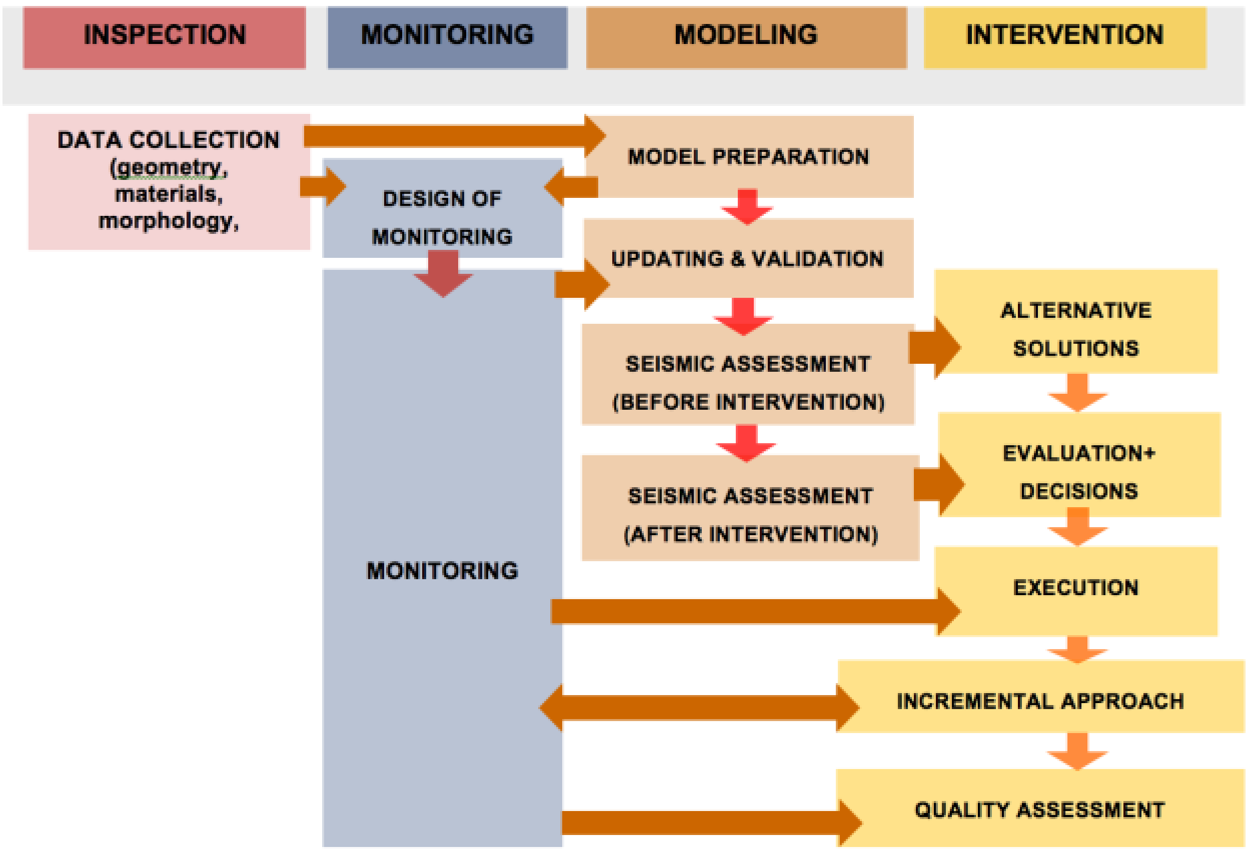
- Measurement of static time-dependent parameters that vary slowly
- Controls of: crack pattern, activation of collapse mechanisms, state of stress and strain, variation of environmental parameters, ...
- Local controls and damage identification

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

SHM: APPLICATION TO CH BUILDINGS

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



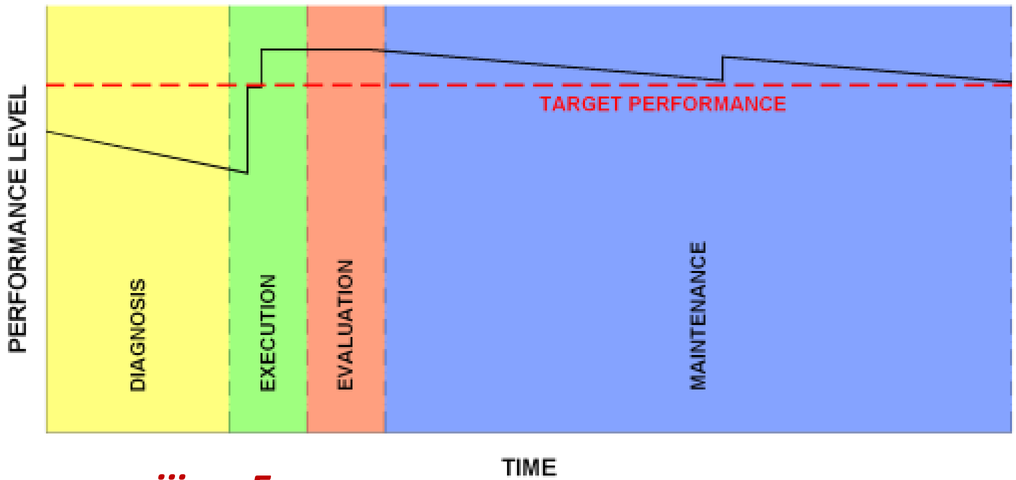
Work Package 9, Knowledge based assessment, NIKER Project - EU FP7

SHM: APPLICATION TO CH BUILDINGS

ROLE OF MONITORING

- INVESTIGATION PHASE
- INTERVENTION PHASE
- EVALUATION PHASE
- MAINTENANCE PHASE

Work Package 9, Knowledge based assessment, NIKER Project - EU FP7



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

IV. MAINTENANCE

- Long-term monitoring program
- Assessment of long-term effectivness and durability of interventions
- Quality control plans, maintenence works and corrective measures

SHM: APPLICATION TO CH BUILDINGS

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

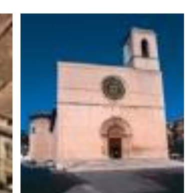
APPLICATION OF AN INCREMENTAL APPROACH TO THE EXECUTION OF STRENGTHENING INTERVENTIONS USING SHM BEFORE, DURING AND AFTER THE IMPLEMENTATION, VALIDATING EVENTUALLY THEIR EFFECTIVENESS


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








SHM: APPLICATION TO CH BUILDINGS

MONITORING SYSTEMS INSTALLED AND MANAGED BY UNIVERSITY OF PADOVA

ARENA OF VERONA (VR)	
INSTALLATION PERIOD	December 2011
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Alternative to the execution of interventions

CANSIGNORIO STONE TOMB (VR)	
INSTALLATION PERIOD	December 2006
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Structural controls before, during and after interventions

SCROVEGNI CHAPEL (PD)	
INSTALLATION PERIOD	October 2013
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Vulnerability assessment/state of damage control

S. SOFIA CHURCH (PD)	
INSTALLATION PERIOD	1999 (1st installation); 2008 (1st upgrade); 2010 (2nd upgrade)
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Structural controls before, during and after interventions

MONITORING SYSTEMS INSTALLED AND MANAGED BY UNIVERSITY OF PADOVA

L'AQUILA CASE STUDIES: POST-EARTHQUAKE CONTROLS

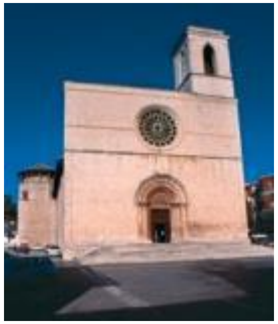
CIVIC TOWER (AQ)	
INSTALLATION PERIOD	July 2010
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls

SPANISH FORTRESS (AQ)	
INSTALLATION PERIOD	December 2009
SHM TYPOLOGY	Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls

S.MARCO CHURCH (AQ)	
INSTALLATION PERIOD	August 2009
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls

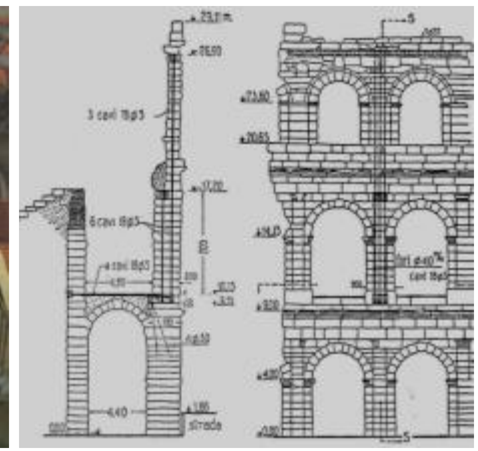
S.BIAGIO/S.GIUSEPPE CHURCH(AQ)	
INSTALLATION PERIOD	December 2010
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls

S.AGOSTINO CHURCH (AQ)	
INSTALLATION PERIOD	July 2010
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls



S.SILVESTRO CHURCH (AQ)	
INSTALLATION PERIOD	July 2010
SHM TYPOLOGY	Static/Dynamic system
PURPOSE OF MONITORING	Post-earthquake controls

i. 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

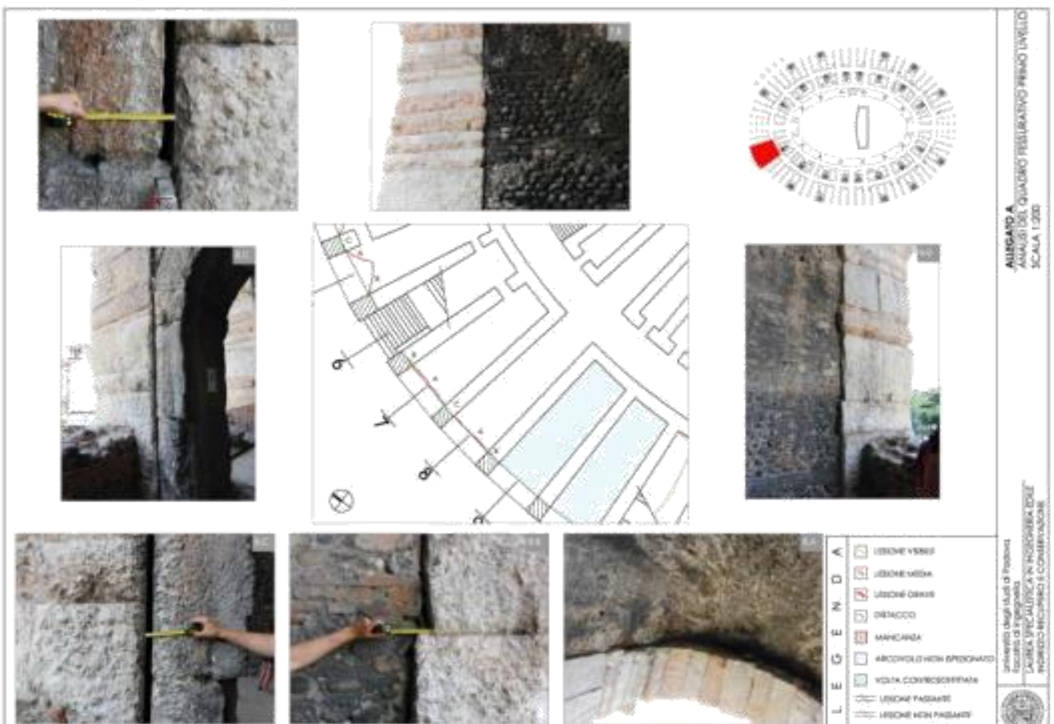
HISTORICAL NOTES - PAST INTERVENTIONS

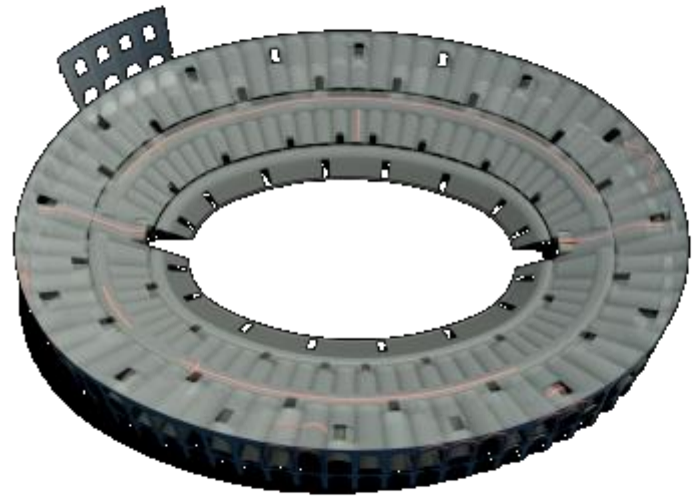
- I century: construction of the amphitheater
- XII century: collapse of the outer ring
- 1939: First intervention on the ‘Wing’: buttresses construction before WWII
- 1953: Second intervention on the ‘Wing’ designed by Eng. Morandi: insertion of post-tensioned steel cables along the pillars

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



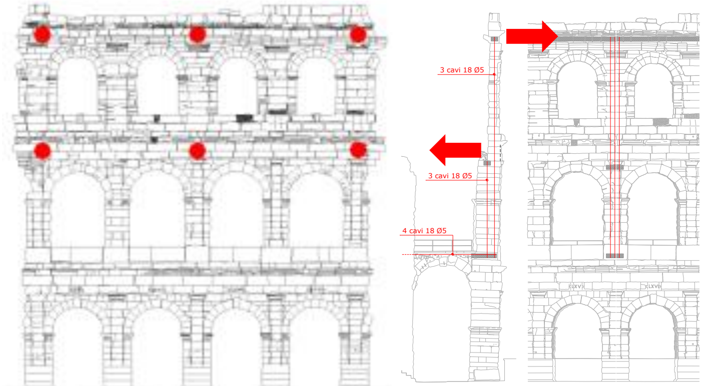


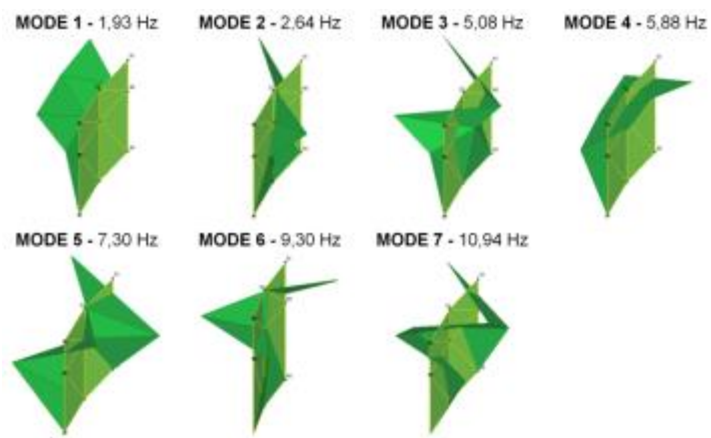
Main structural problems:

- 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

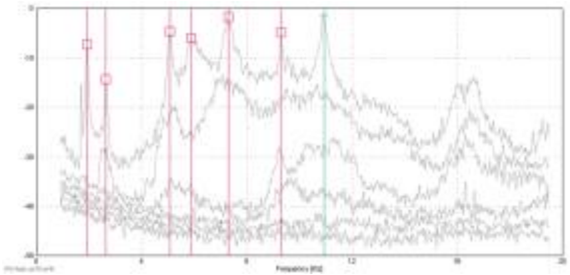
b. OPERATIONAL MODAL ANALYSIS (OMA):

- 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 lenght: 21’51” sec
- System identification: decimation; segment length 2048 points, 66.67% overlap; selected methods: FDD and EFDD

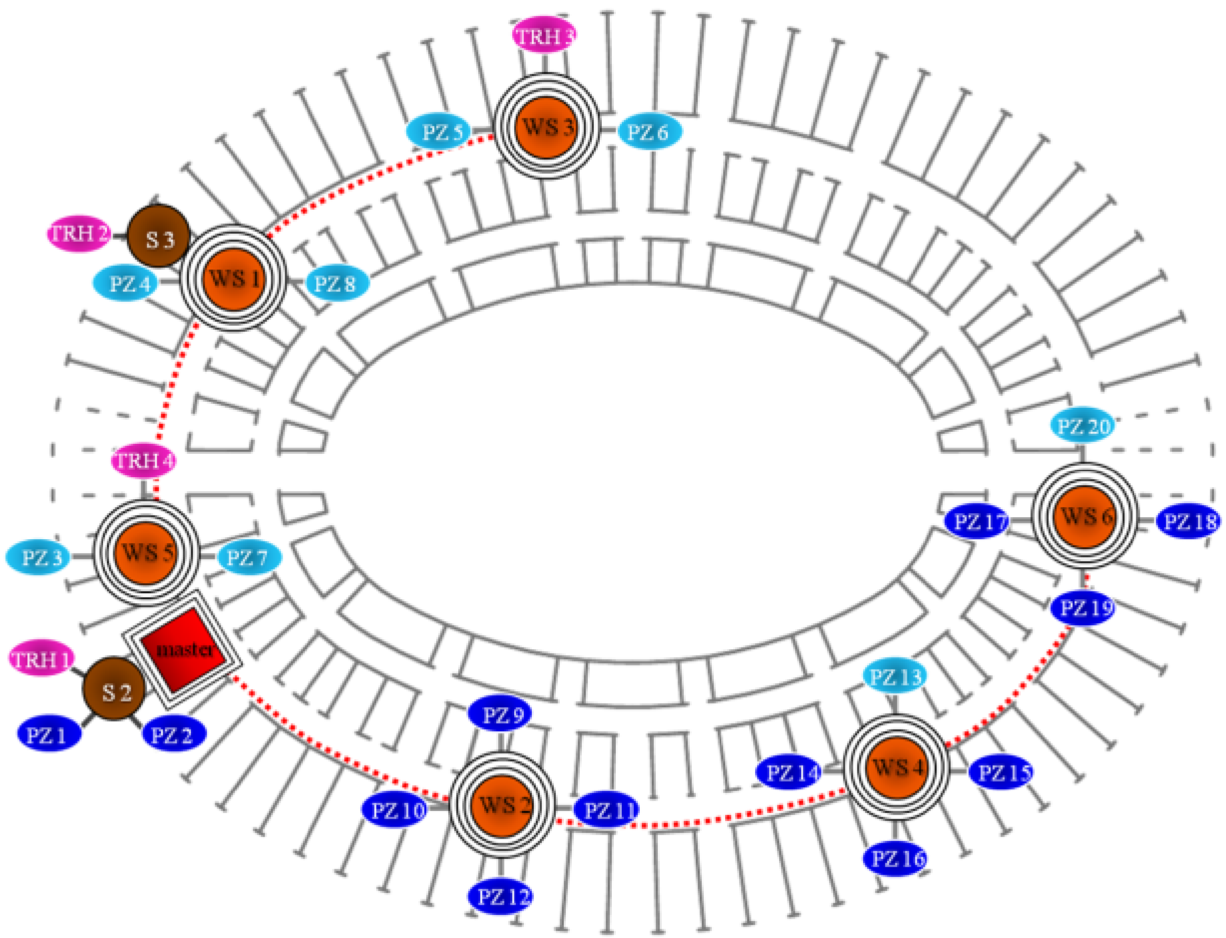




MODE	AVT - Oct 2011				FVT - 1996		AVT vs. FVT	
	FDD	EFDD		MAC			Average error [%]	
	f [Hz]	f [Hz]	ξ [%]		f [Hz]	ξ [%]	f	ξ
1	1,93	1,92	1,36	1	1,92	1,4	0	2,94
2	2,64	2,65	1,12	0,99	2,61	1,3	1,51	16,07
3	5,08	5,08	1,07	0,99	4,83	1,8	4,92	68,22
4	5,88	5,98	3,86	0,99	5,87	6,9	1,84	78,76
5	7,30	7,29	2,07	0,99	7,10	2,3	2,61	11,11
6	9,30	9,30	0,43	0,99	8,62	1,1	7,31	155,81
7	10,94	10,92	1,06	0,99	10,65	2,6	2,47	145,28



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(da 10,000 Hz): 0.00008 m/s²
Operating temperature : -45÷82 °C

Static Monitoring

20 Displacement transducers

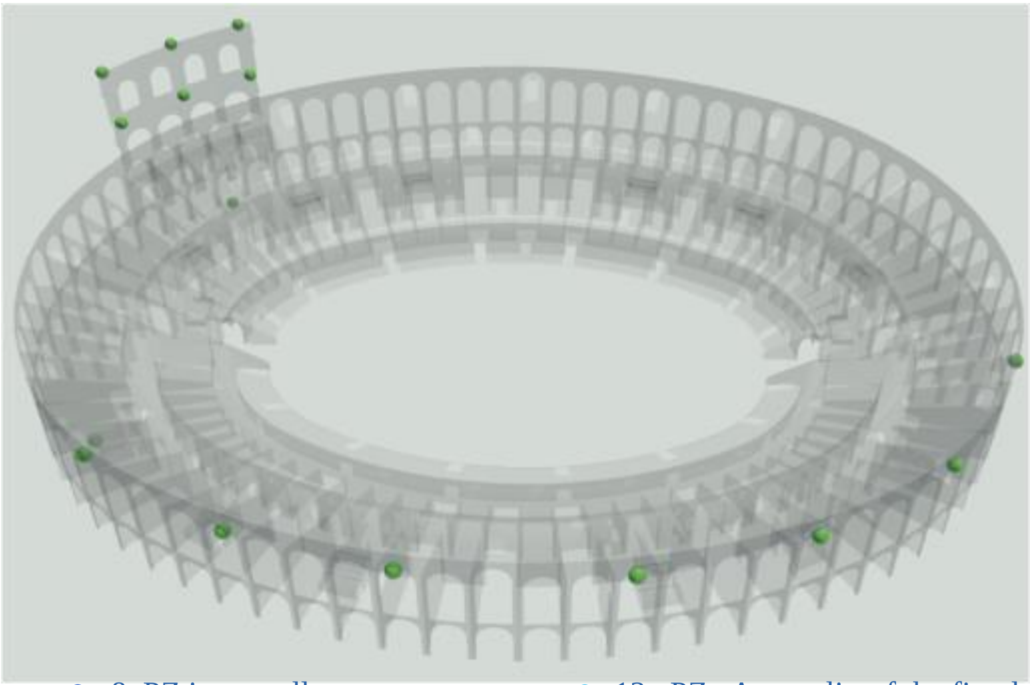
Voltage: 0÷10 V
Measurement range: 10 cm
Hysteresis: < 0.01 mm
Operating temperature:-30÷100 °C

Environmental Monitoring

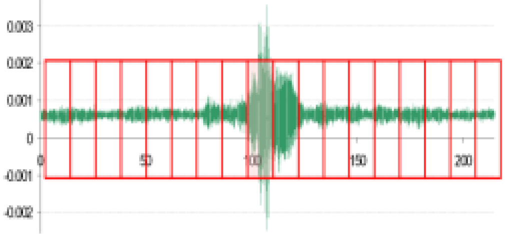
4 Temperature/RH

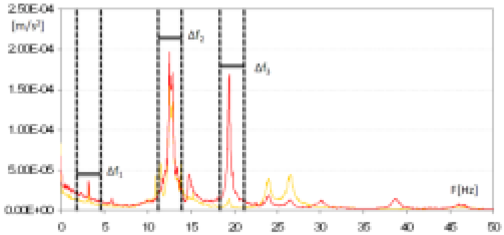
Voltage: 0÷10 V
Precision: +/- 2 % RH
+/- 0.2 °C
Measurement range: 0÷100% RH
- 20/0÷50 °C

Arena of Verona: the monitoring system



- 8 PZ inner gallery
- 12 PZ «Arcovoli» of the first level





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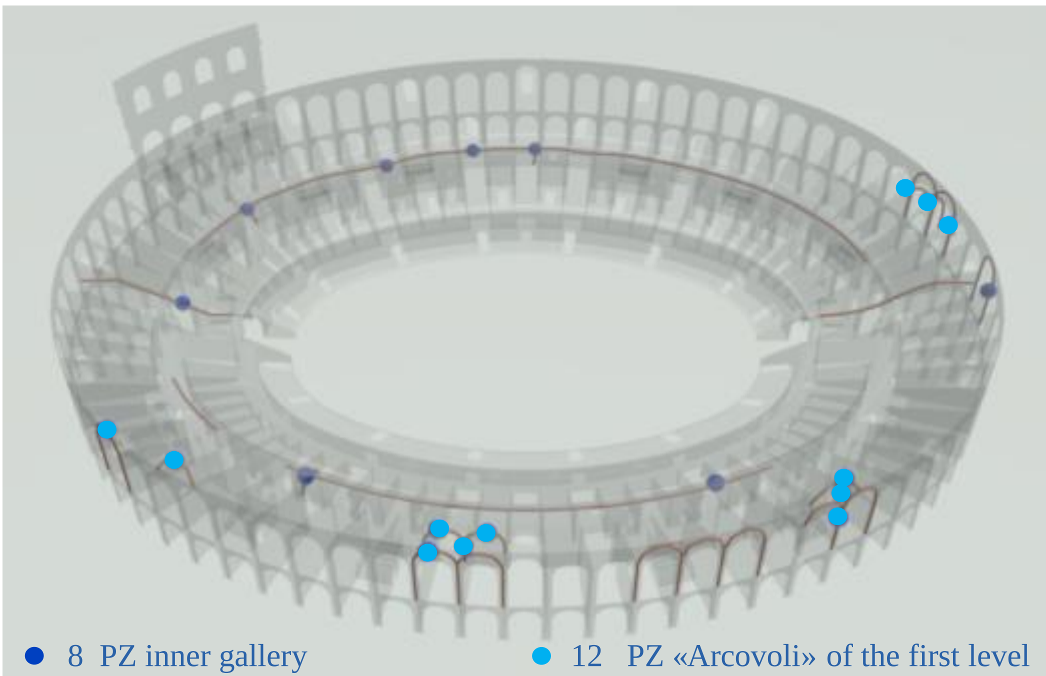
ARENA OF VERONA: THE MONITORING SYSTEM



DYNAMIC MONITORING

16 SINGLE-AXIS ACCELEROMETERS

SENSITIVITY: 1019.4 MV/(M/S²)
FREQUENCY RANGE (± 10 %): 0.1÷2000 HZ
RESOLUTION(DA 10,000 HZ): 0.00008 M/S²
OPERATING TEMPERATURE : -45÷82 °C

STATIC MONITORING

20 DISPLACEMENT TRANSDUCERS

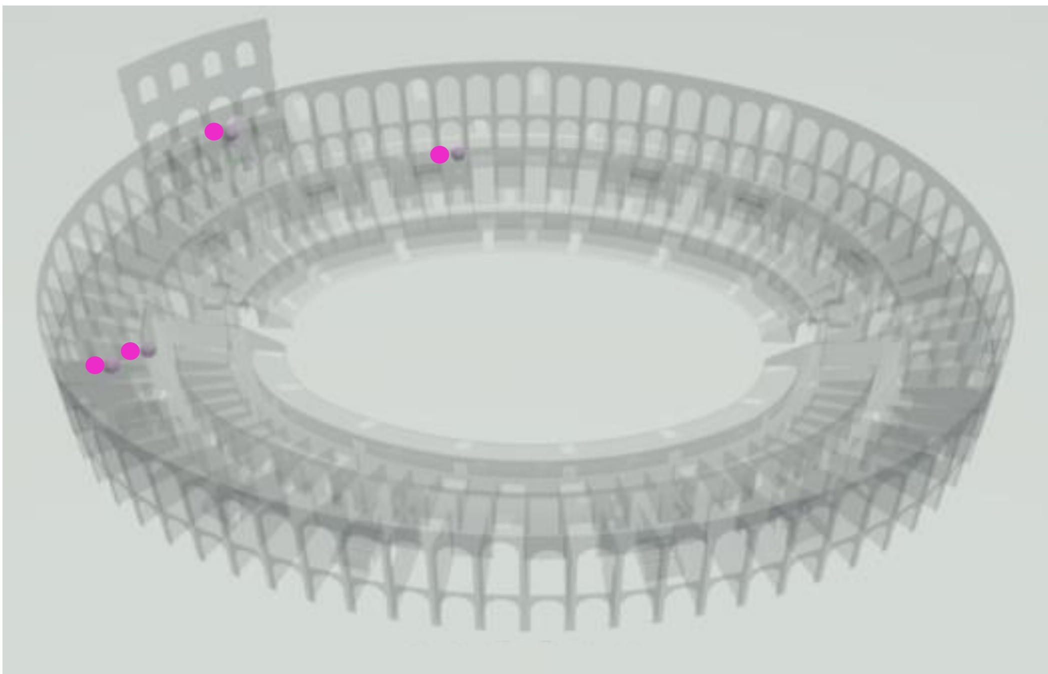
VOLTAGE: 0÷10 V
MEASUREMENT RANGE: 10 CM
HYSTERESIS: < 0.01 MM
OPERATING TEMPERATURE:-30÷100 °C

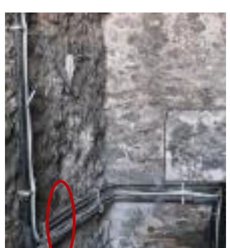
ENVIRONMENTAL MONITORING

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: THE MONITORING SYSTEM





DYNAMIC MONITORING

16 SINGLE-AXIS ACCELEROMETERS

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RESOLUTION(DA 10,000 HZ): 0.00008 M/S²
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STATIC MONITORING

20 DISPLACEMENT TRANSDUCERS

VOLTAGE: 0÷10 V
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ENVIRONMENTAL MONITORING

4 TEMPERATURE/RH

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PRECISION: +/- 2 % RH
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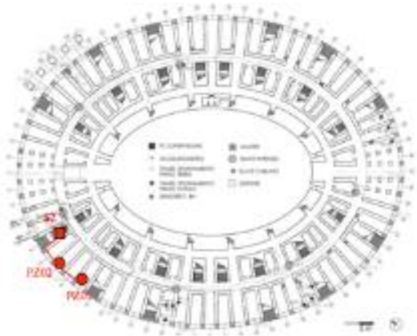
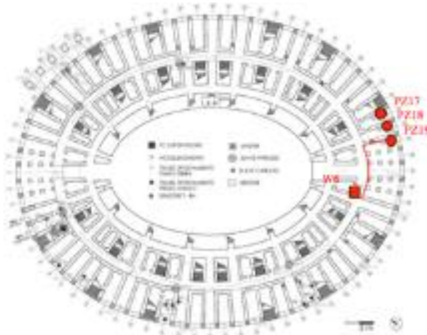
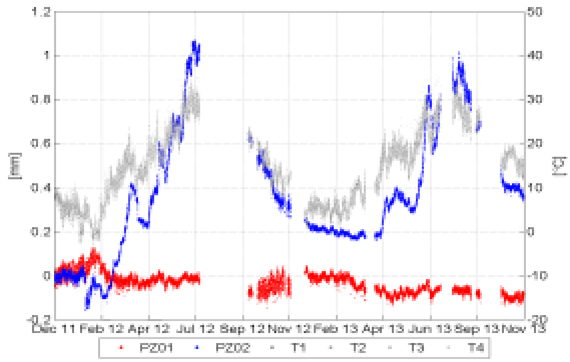
MEASUREMENT RANGE: 0÷100% RH
- 20/0÷50 °C

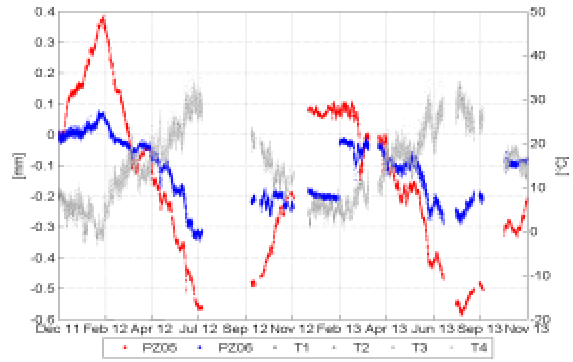
ARENA OF VERONA: STATIC MONITORING RESULTS (2 YEARS)

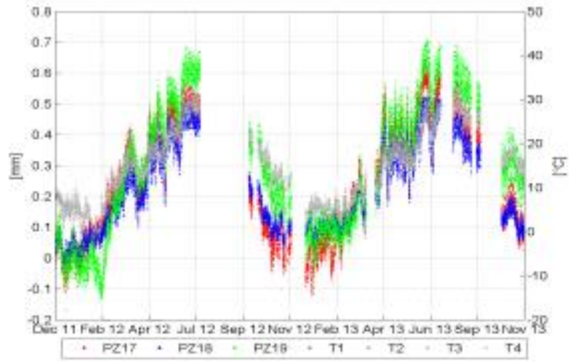




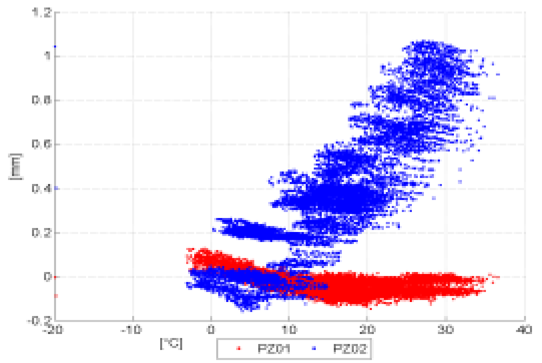
CRACK OPENING VS. TIME

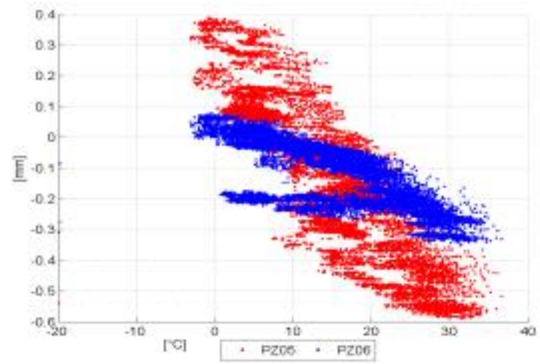


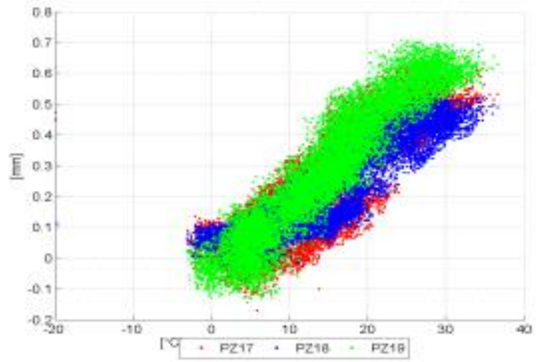




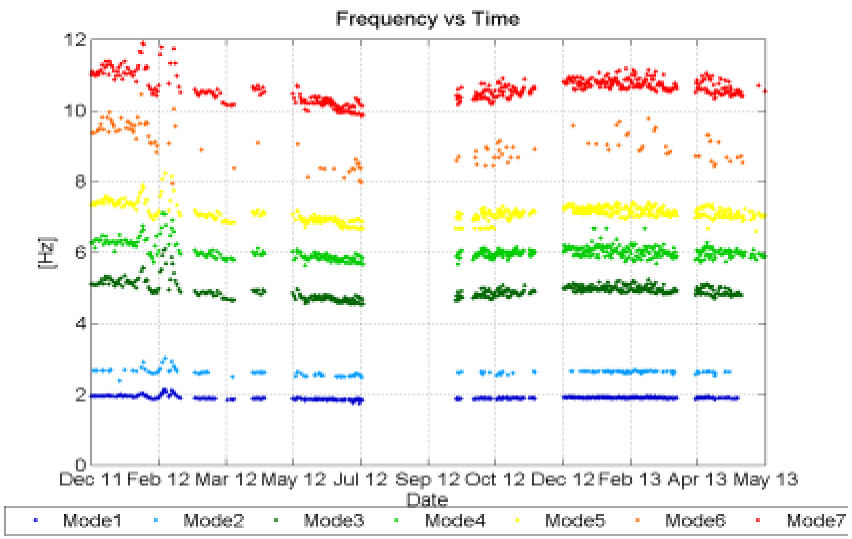
CRACK OPENING VS. TEMERATURE

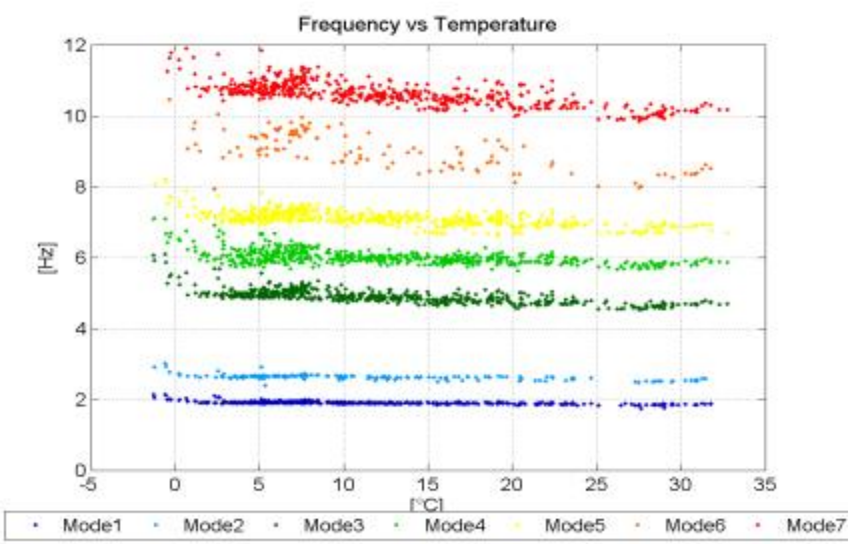






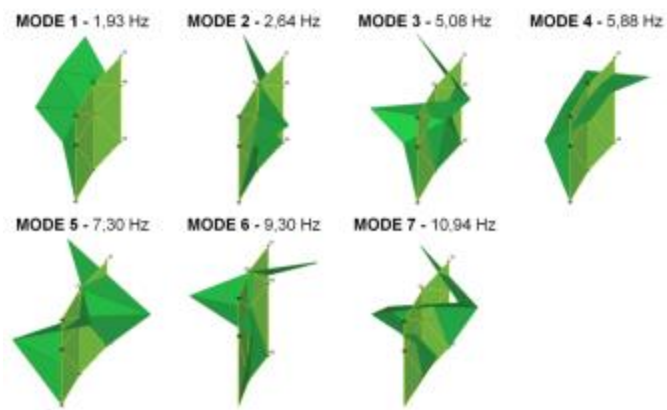
ARENA OF VERONA - ALA: DYNAMIC MONITORING RESULTS (2 YEARS)





STATISTICAL RESULTS (FREQUENCIES - DAMPING - MAC)

Mode	f_{mean} [Hz]	f_{std} [Hz]	ξ_{mean} [%]	ξ_{std} [%]	MAC_{mean} [%]	MAC_{min} [%]
1	1,902	0,051	0,977	0,359	90,66	70,30
2	2,621	0,097	0,903	0,326	89,10	70,55
3	4,888	0,240	1,037	0,226	94,15	70,98
4	6,016	0,232	5,247	1,527	96,62	74,25
5	7,091	0,253	1,933	0,772	94,25	70,11
6	9,028	0,575	0,961	0,365	86,93	70,01
7	10,555	0,384	1,119	0,229	94,91	70,03

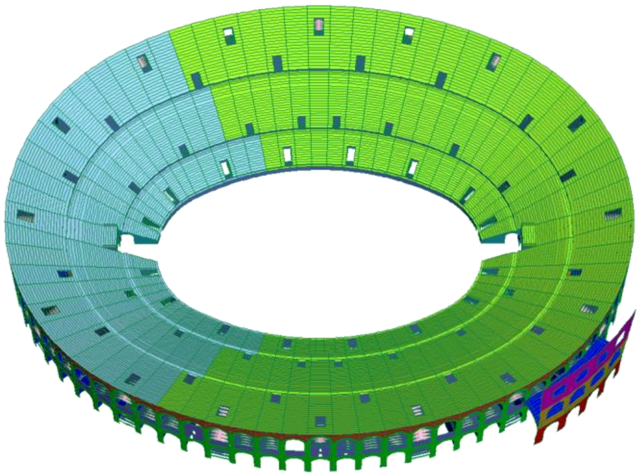


- Natural frequencies of the Arena's wing are rather stable during the analysed monitoring period (Dec 2011 - Dec 2013)
- Relationship between frequencies and temperature:
  - T > 5°C → frequencies are stable
  - T < 5°C → frequencies tend to increase

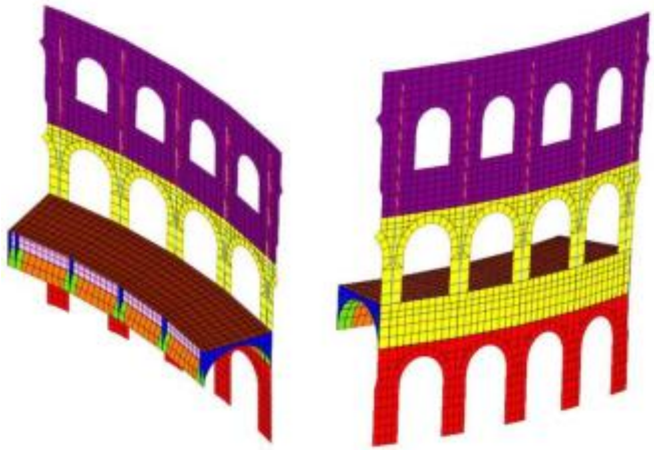
SHM FOR MODEL UPDATING

APPLICATION TO VERONA CASE STUDIES: ARENA

- 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, ect.



FE MODEL OF THE ARENA'S WING



CALIBRATION PROCEDURE

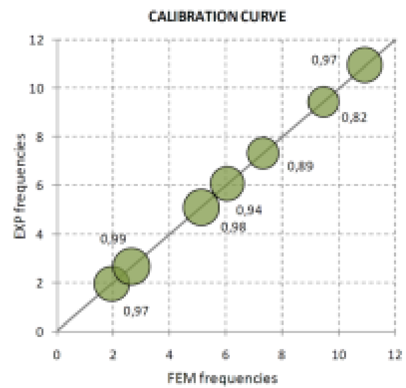
- Identification of morphology and materials
- Definition of initial values of elastic mechanical properties
- Iterative variation of mechanical properties/boundary conditions within a predefined range until reaching the final calibration

APPLICATION TO VERONA CASE STUDIES: ARENA

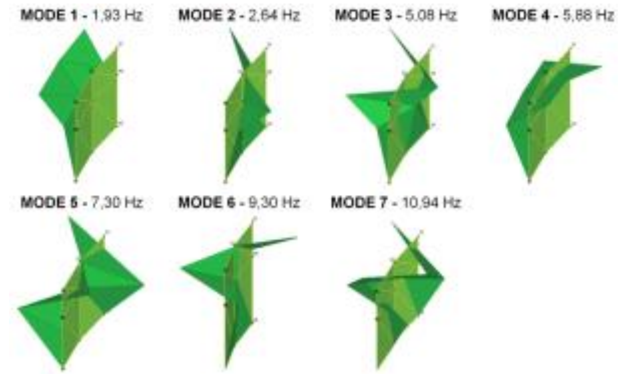
MODEL UPDATING RESULTS

MODAL MATCHING: EXP/FEM RESULTS

MODE	Type	f_{EXP} [Hz]	f_{FEM} [Hz]	Average error ε [%]	MAC $(\{\psi^{EXP}\},\{\psi^{FEM}\})$
1	1st out-of-plane bend.	1,924	1,924	|0,01|	0,973
2	1st torsional	2,666	2,640	|1,00|	0,993
3	2nd torsional	5,103	5,122	|0,36|	0,984
4	2nd out-of-plane bend.	6,086	6,054	|0,53|	0,936
5	3rd torsional	7,308	7,323	|0,20|	0,886
6	4th torsional	9,434	9,464	|0,32|	0,821
7	5th torsional	10,970	10,944	|0,24|	0,973

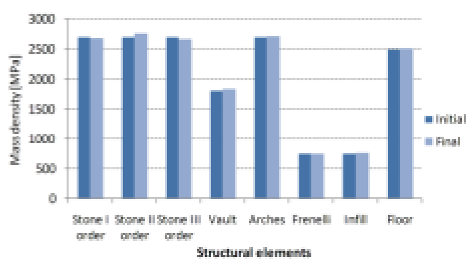


EXPERIMENTAL MODE SHAPES

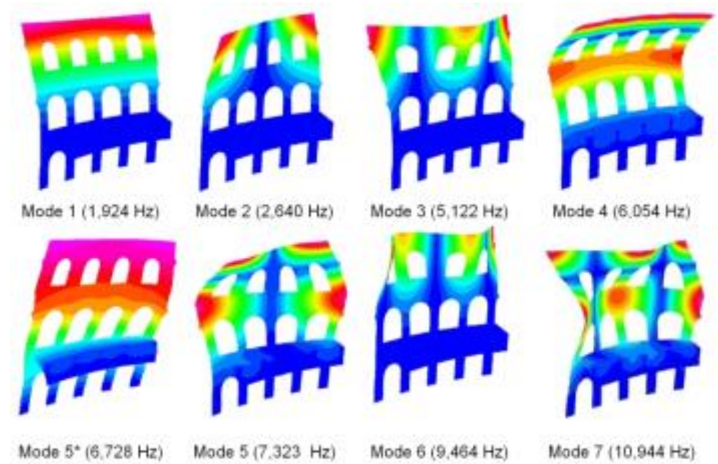


VARIATION OF UPDATING PARAMETERS

Structural element	ELASTIC MODULUS [MPa]			MASS DENSITY [kg/m³]		
	Initial	Final	Diff. [%]	Initial	Final	Diff. [%]
Stone I order	15000	15223	1.49	2700	2687	-0.48
Stone II order	15000	16174	7.82	2700	2752	1.92
Stone III order	15000	14443	-3.71	2700	2658	-1.56
Vault	2400	2479	3.27	1800	1830	1.64
Arches	15000	14096	-6.03	2700	2703	0.12
Frenelli	500	477	-4.63	750	750	-0.04
Infill	500	483	-3.48	750	757	0.92
Stone floor	12000	11723	-2,31	2500	2509	0.36



NUMERICAL MODE SHAPES



* in-plane bending mode not identified during AVT and dynamic monitoring

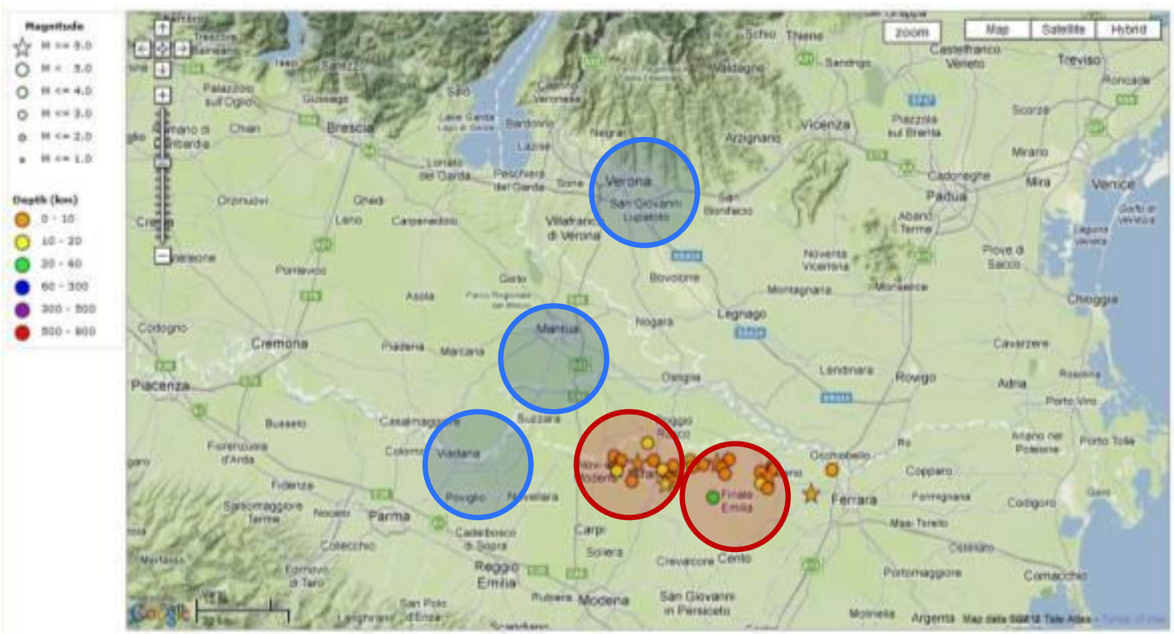
SHM IN CASE OF EXCEPTIONAL EVENTS

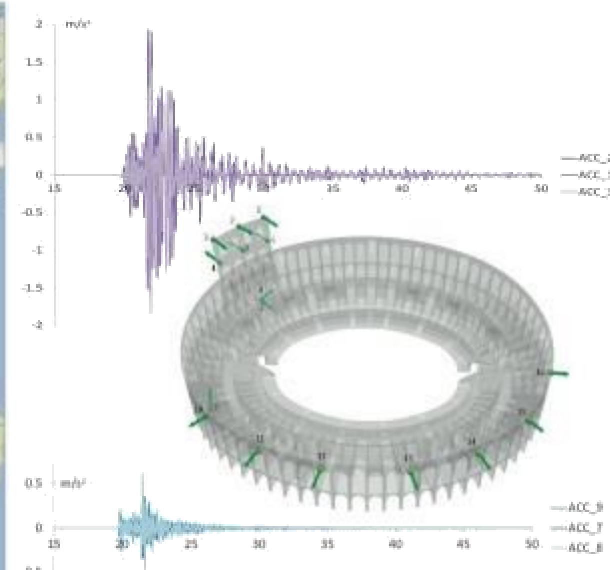
APPLICATION TO VERONA CASE STUDY: ROMAN ARENA

5 Main seismic events (with several aftershoks) 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

Seismic events	UTC	Magnitude	Depth	GPS Coordinates	
				Latitude	Longitude
1	2012-01-24 23:54:46	4.2	10.3	45.541	10.973
2	2012-01-25 08:06:36	4.9	33.2	44.854	10.538
3	2012-01-27 14:53:13	5.4	60.8	44.483	10.033
4	2012-05-20 02:03:53	5.9	6.3	44.890	11.230
5	2012-05-29 07:00:03	5.8	10.2	44.851	11.086



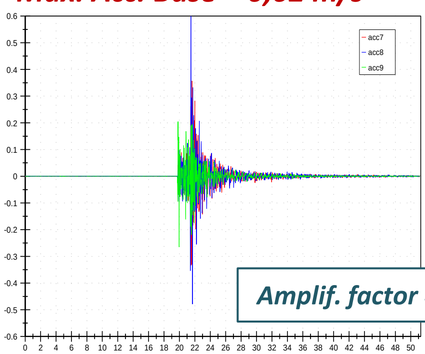


ANALYSIS OF GROUND MOTION RECORDS

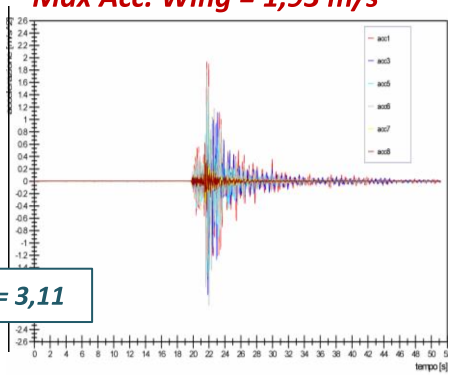
MAIN SHOCK: 25 JANUARY 2012

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

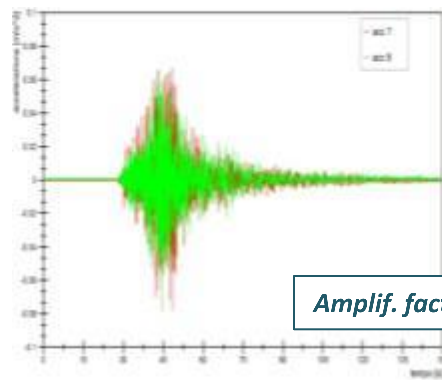


Amplif. factor = 3,11

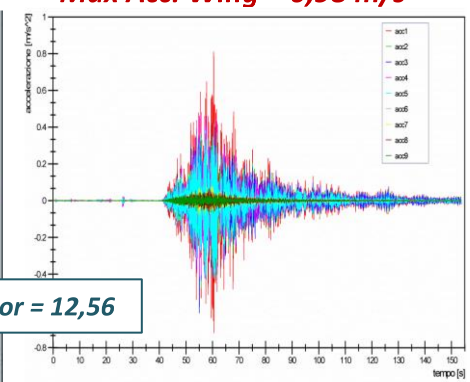
MAIN SHOCK: 29 MAY 2012

Pianura Padana-Emiliana (MO) 2012-05-29 07:00:03
Magnitude: 5.8
Depth 10.2 Km
Distance: 75 Km

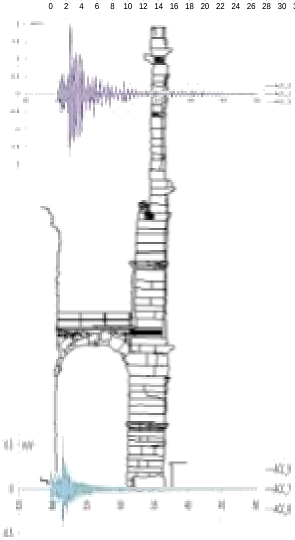
Max. Acc. Base = 0,08 m/s²



Max Acc. Wing = 0,98 m/s²

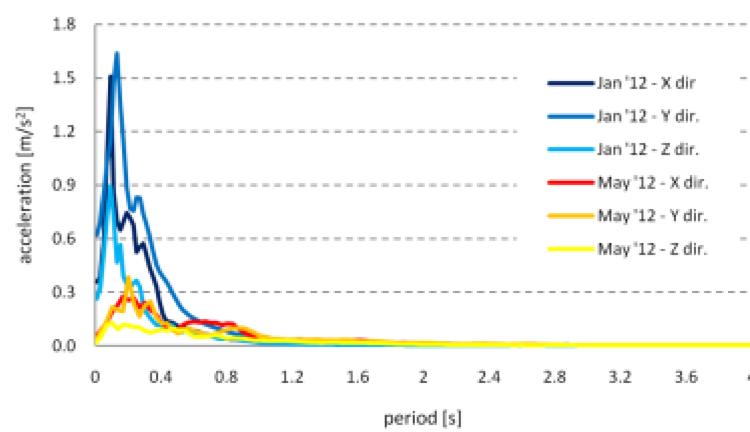


Amplif. factor = 12,56



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

Seismic event	BASE	TOP WING		TOP AMPHITHEATER	
	PGA [m/s²]	Max. Acc. [m/s²]	Amplif. factor	Max Acc. [m/s²]	Amplif. factor
25/01/2012	0,619	1,93	3,11	1,251	2,02
29/05/2012	0,078	0,98	12,56	0,40	5,13



Modal parameters identification

MAIN SHOCK: 25 JANUARY 2012 → Dynamic identification of modal parameters before, during and after the seismic event

OMA TECHNIQUES NOT RELIABLE

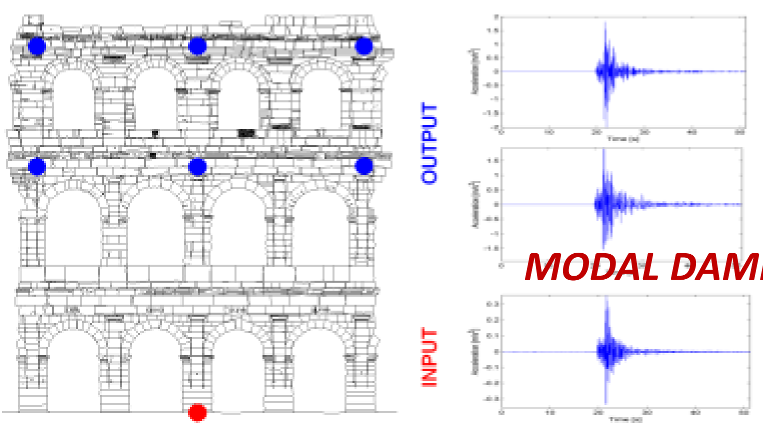
- Input is not a whithe noise stochastic process
- Earthquake is a nonstationary signal
- Frequency spectrum of the transient input biases modal parameter estimation

→ **OMAX COMBINED OMA/EMA**

Data-driven reference-based deterministic-stochastic Subspace Identification (CSI/ref) method

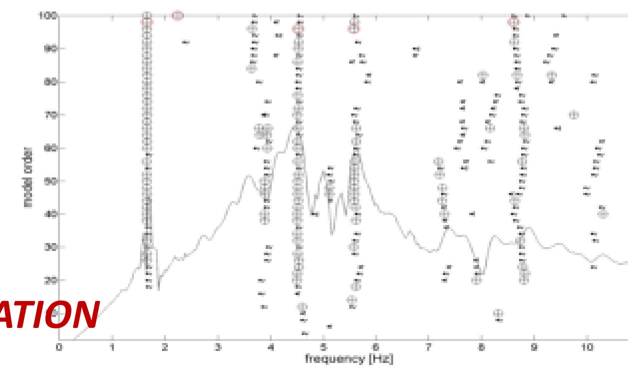
NATURAL FREQUENCIES VARIATION

FULL-SCALE FORCED VIBRATION TEST ON THE ARENA'S WING



MODAL DAMPING VARIATION

STABILIZATION DIAGRAM



MODAL PARAMETERS IDENTIFICATION

MAIN SHOCK: 25 JANUARY 2012

Dynamic identification of modal parameters before, during and after the seismic event

OMA TECHNIQUES NOT RELIABLE

- INPUT IS NOT A WHITHE NOISE STOCHASTIC PROCESS
- EARTHQUAKE IS A NONSTATIONARY SIGNAL
- FREQUENCY SPECTRUM OF THE TRANSIENT INPUT BIASES MODAL PARAMETER ESTIMATION

OMAX COMBINED OMA/EMA

DATA-DRIVEN REFERENCE-BASED DETERMINISTIC-STOCHASTIC SUBSPACE IDENTIFICATION (CSI/REF) METHOD

FULL-SCALE FORCED VIBRATI
IN

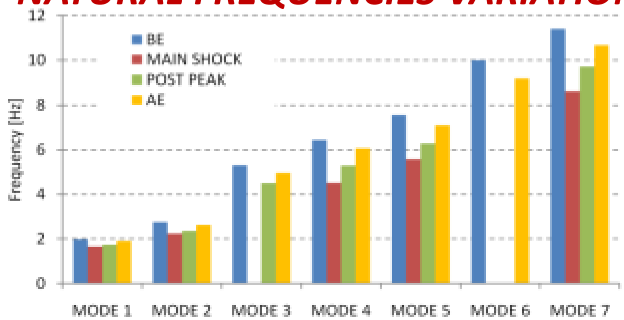
FREQUENCY VARIATIONS							
MODE	BE [Hz]	MS [Hz]	PP [Hz]	AE [Hz]	f change (BE-MS)	f change (BE-AE)	MAC $(\{\psi^{BE}\},\{\psi^{MS}\})$
1	1,98	1,66	1,73	1,89	-16,28%	-4,44%	0,9998
2	2,75	2,24	2,35	2,62	-18,63%	-5,11%	0,9664
3	5,31	n.i*	4,50	4,97	/	-6,94%	/
4	6,44	4,52	5,29	6,07	-29,77%	-6,09%	0,9933
5	7,57	5,59	6,28	7,10	-26,15%	-6,55%	0,9372
6	10,00	n.i*	n.i*	9,18	/	-8,89%	/
7	11,40	8,62	9,71	10,67	-24,34%	-6,78%	0,9581

*not identified

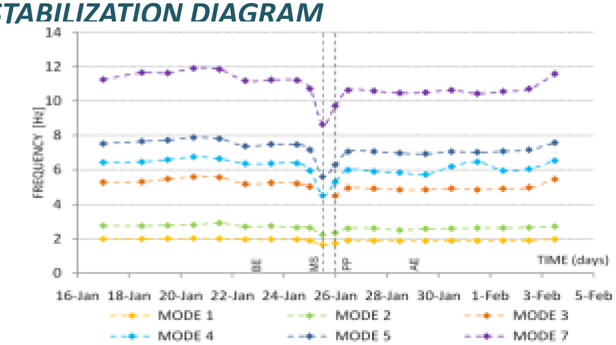
DAMPING RATIO VARIATIONS						
MODE	BE [%]	MS [%]	PP [%]	AE [%]	ξ change (BE-MS)	ξ change (BE-AE)
1	1.17	2.71	2.18	0.96	+131.47%	-22.25%
2	1.11	5.11	2.67	0.82	+361.43%	-35.21%
3	1.03	n.i*	1.30	0.96	/	-7.10%
4	6.44	1.97	3.75	4.87	-69.45%	-32.23%
5	2.81	6.64	4.38	2.30	+136.19%	-22.44%
6	0.95	n.i*	n.i*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

*not identified

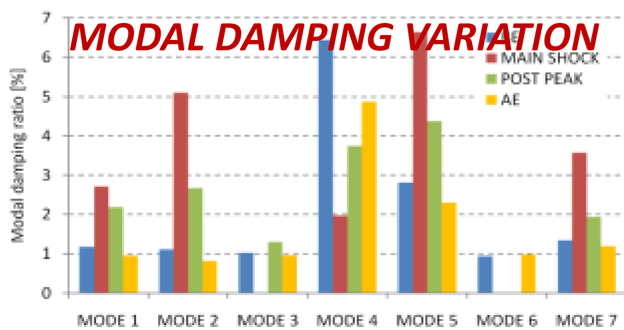
NATURAL FREQUENCIES VARIATION

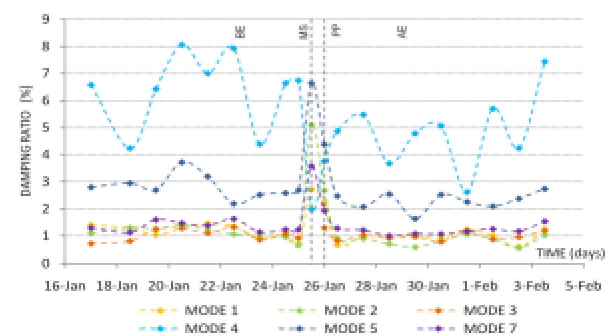


TABILIZATION DIAGRAM

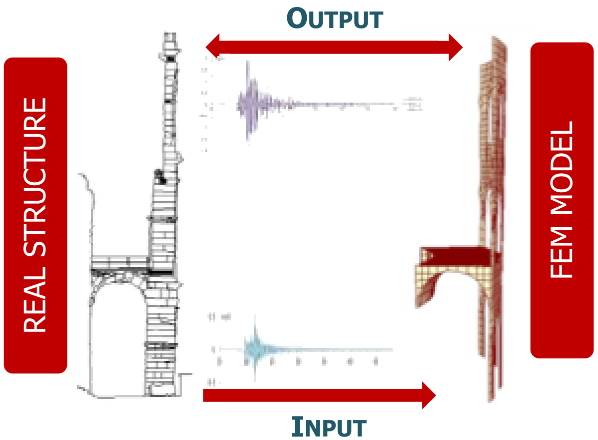


MODAL DAMPING VARIATION





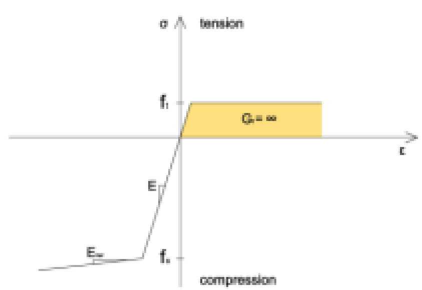
NUMERICAL SIMULATION



- 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

Material	Tensile strength f_t [MPa]	Fracture energy G_f [N/mm]	Compressive strength f_c [MPa]	Elastic Hardening E_{har} [MPa]
Stone blocks masonry	0,13	∞	3,00	3,00
Opus coementicium (vaults and arches)	0,13	∞	3,00	3,00
Infill of vaults	linear elastic			
Stone floor	linear elastic			



DAMPING COEFFICIENT CALIBRATION

From dynamic identification during the earthquake

MODE	BE [%]	MS [%]	PP [%]	AE [%]	ξ change (BE-MS)	ξ change (BE-AE)
1	1.17	2.71	2.18	0.96	+131.47%	-22.25%
2	1.11	5.11	2.67	0.82	+361.43%	-35.21%
3	1.03	n.i*	1.30	0.96	/	-7.10%
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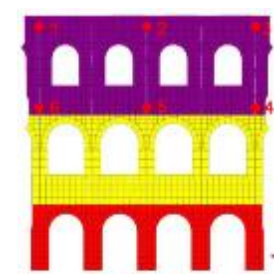
5	2.81	6.64	4.38	2.30	+136.19%	-22.44%
6	0.95	n.i*	n.i*	0.99	/	+3.71%
7	1.34	3.57	1.93	1.19	+166.83%	-12.51%

DAMPING RATIO VARIATIONS

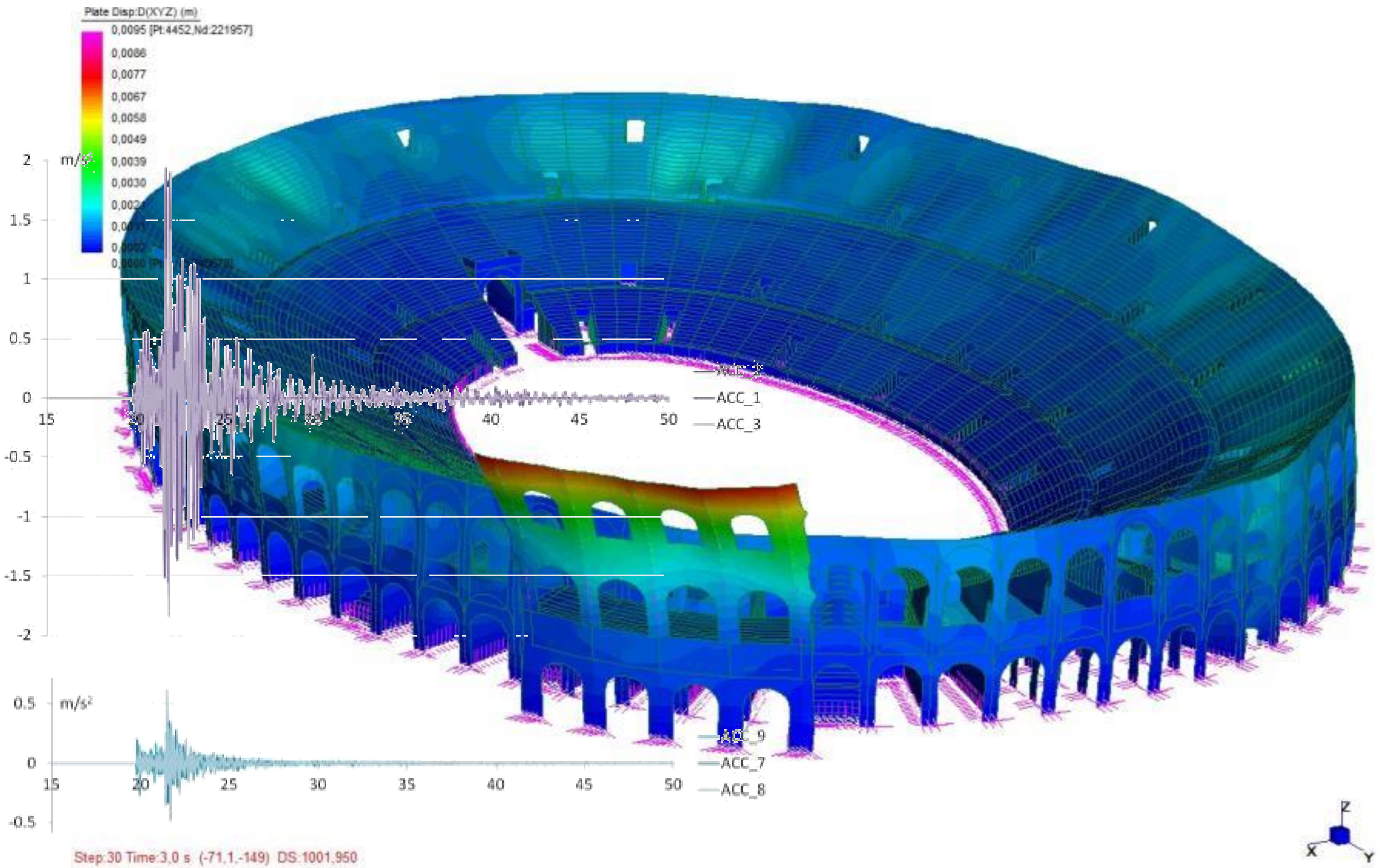
*not identified



Reyleigh damping: $C = aM + bK$

a, b Reyleigh coefficients calculated on the estimated damping ratio ξ

NUMERICAL SIMULATION



ii. CANSIGNORIO STONE TOMB: SHM TO VALIDATE THE EFFECTIVENESS OF INTERVENTIONS

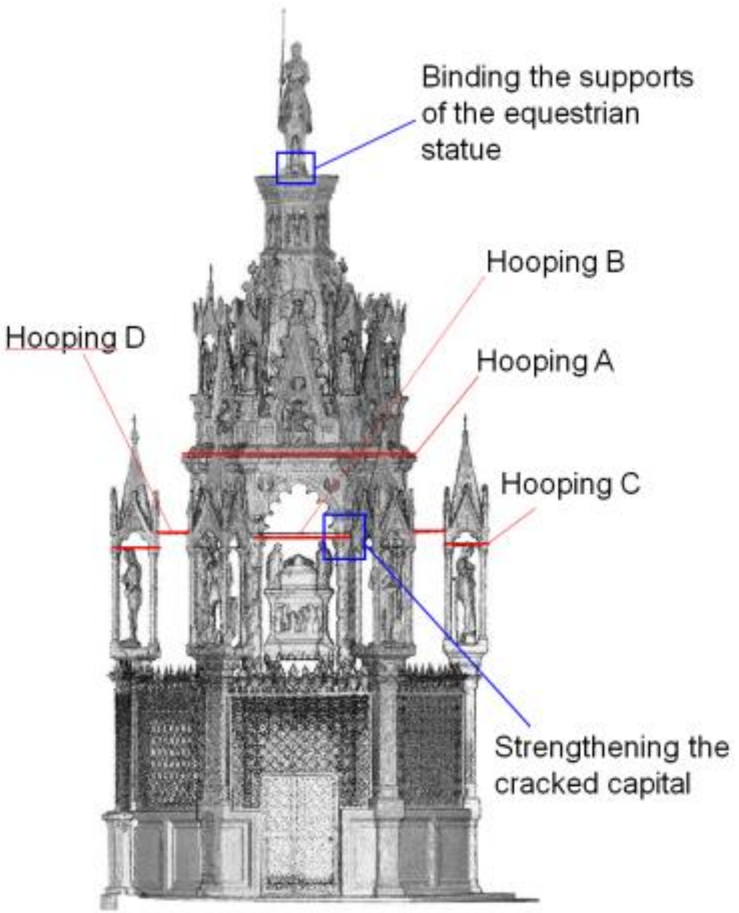
GEOMETRIC AND MATERIAL FEATURES

- 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;
- from1676: periodical restoration works;
- 1915-19, 1940-45: anti-aircraft protections;
- 2006-08: important consolidation interventions

Cansignorio stone tomb : strengthening intervention (2006-2008)



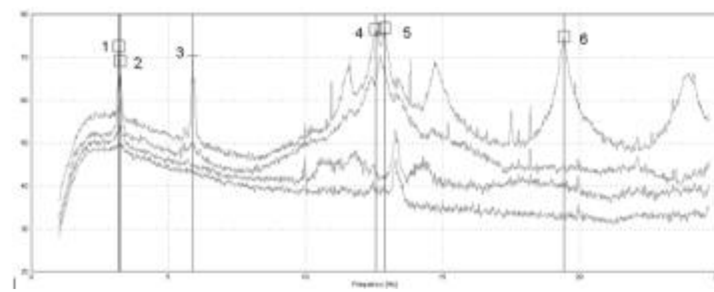
Local and Global interventions

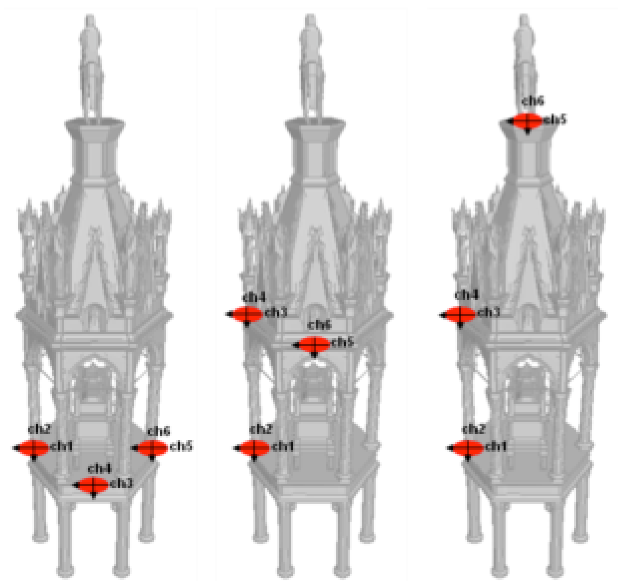
CANSIGNORIO STONE TOMB : PRELIMINARY INSPECTIONS

a. OPERATIONAL MODAL ANALYSIS (OMA):

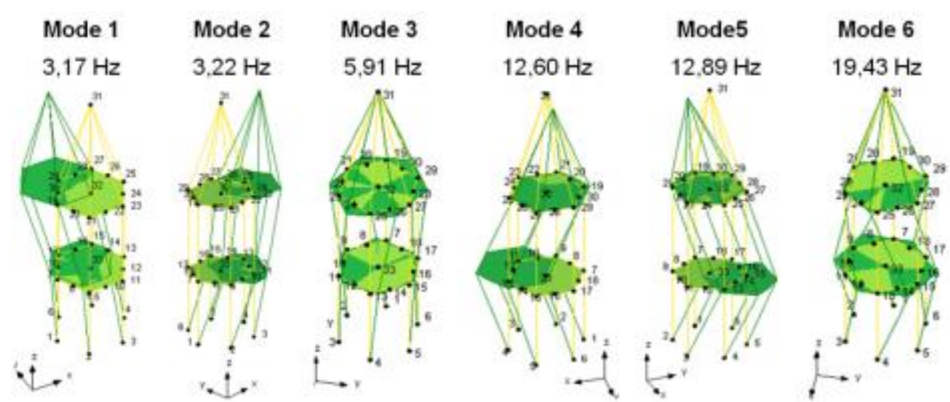
- Definition of the optimal layout of the dynamic system
- Identification of the dynamic behaviour of the monument
- Model updating
- SF 100 Hz; 131'072 points; record lenght: 21'51" sec
- System identification: decimation; segment length 2048 points, 66.67% overlap; selected method: FDD

MODE	FDD [Hz]	Comment
1	3,17	1st bending NS
2	3,22	1st bending EO
3	5,91	1st torsional
4	12,60	2nd bending NS
5	12,89	2nd bending EO
6	19,43	2nd torsional





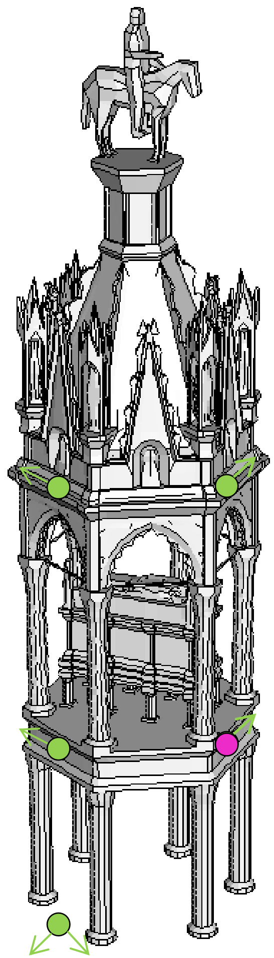
SETUP 1 SETUP 2 SETUP 3

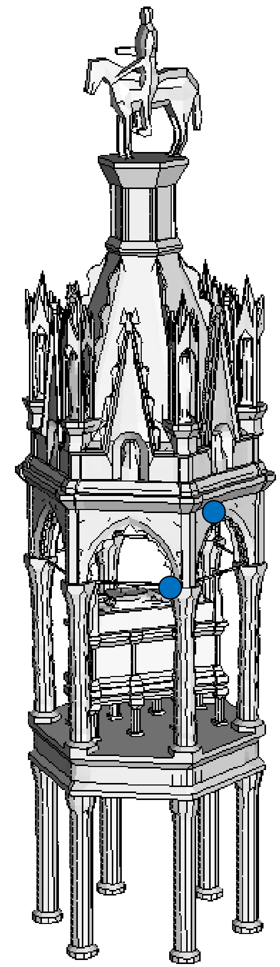


CANSIGNORIO STONE TOMB: THE MONITORING SYSTEM

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 inteventions





DYNAMIC MONITORING

4 SINGLE-AXIS ACCELEROMETERS

SENSITIVITY: 1019.4 MV/(M/S^2)
FREQUENCY RANGE (± 10 %): 0.1÷2000 HZ
RESOLUTION(DA 10,000 HZ): 0.00008 M/S^2
OPERATING TEMPERATURE : -45÷82 °C

STATIC MONITORING

2 DISPLACEMENT TRANSDUCERS

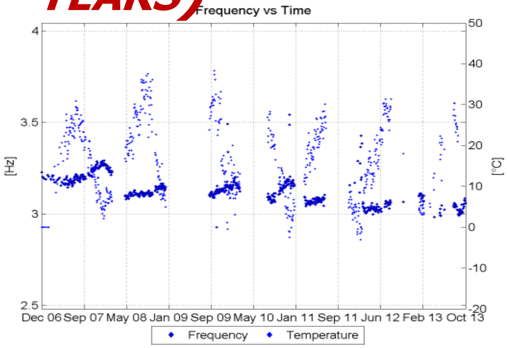
VOLTAGE: 0÷10 V
MEASUREMENT RANGE: 10 CM
HYSTERESIS: < 0.01 MM
OPERATING TEMPERATURE:-30÷100 °C

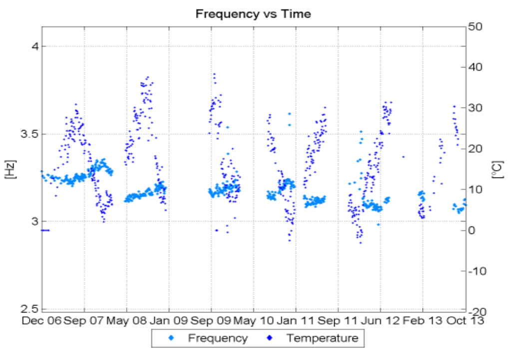
ENVIRONMENTAL MONITORING

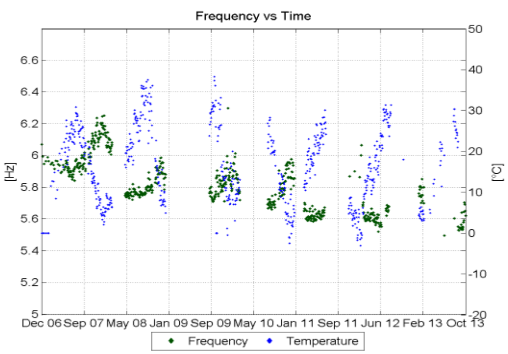
1 TEMPERATURE/RH

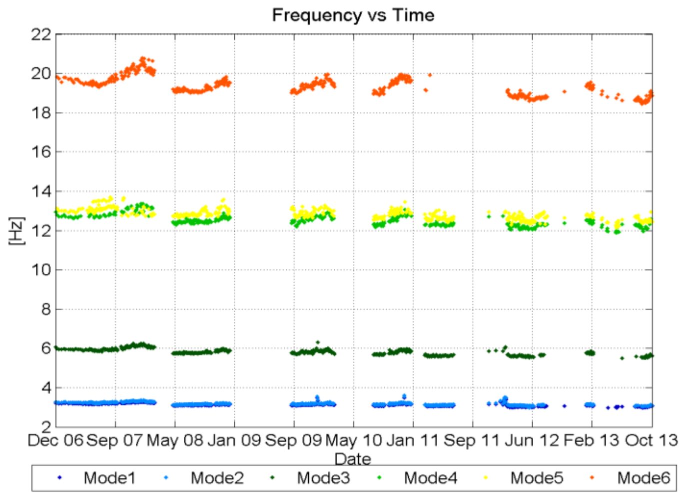
VOLTAGE: 0÷10 V
PRECISION: +/- 2 % RH
+/- 0.2 °C
MEASUREMENT RANGE:
0÷100% RH
- 20/0÷50 °C

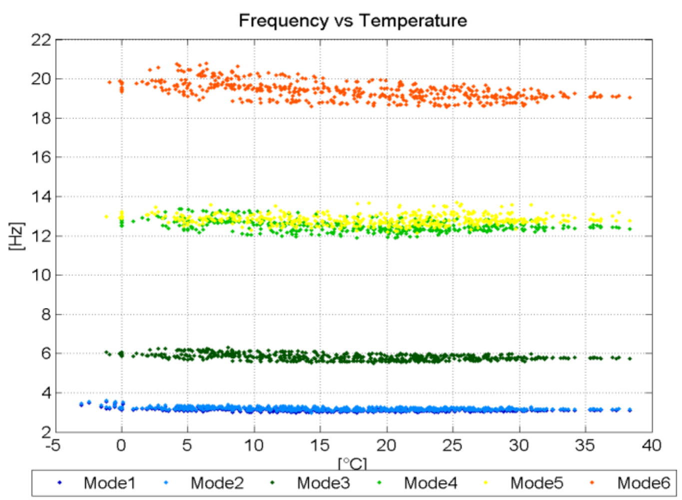
CANSIGNORIO STONE TOMB: NATURAL FREQUENCIES VARIATION (7 YEARS)

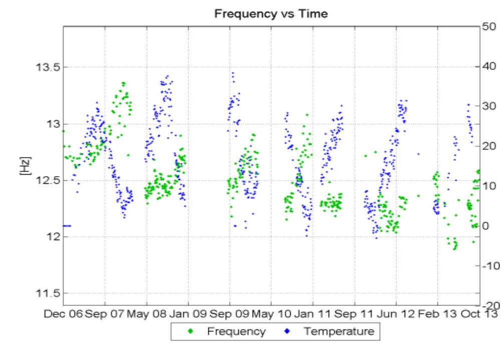


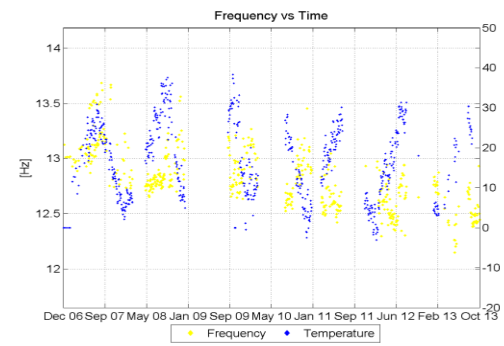


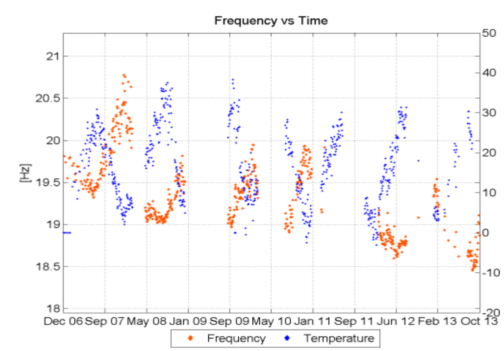






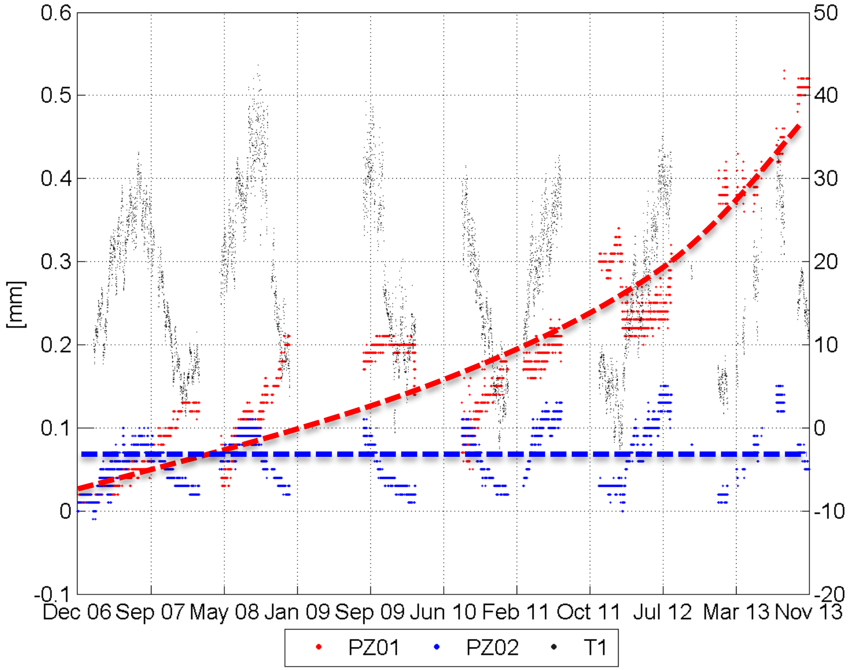




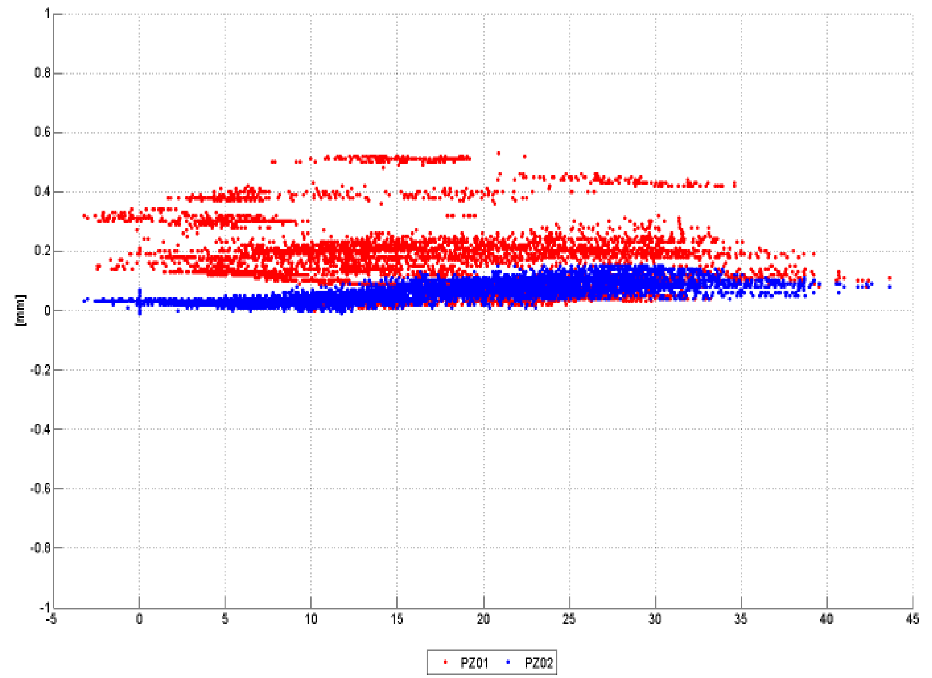


CANSIGNORIO STONE TOMB: CRACKS OPENING (7 YEARS)

CRACK OPENING VS. TIME



CRACK OPENING VS. TEMPERATURE



PZ 01

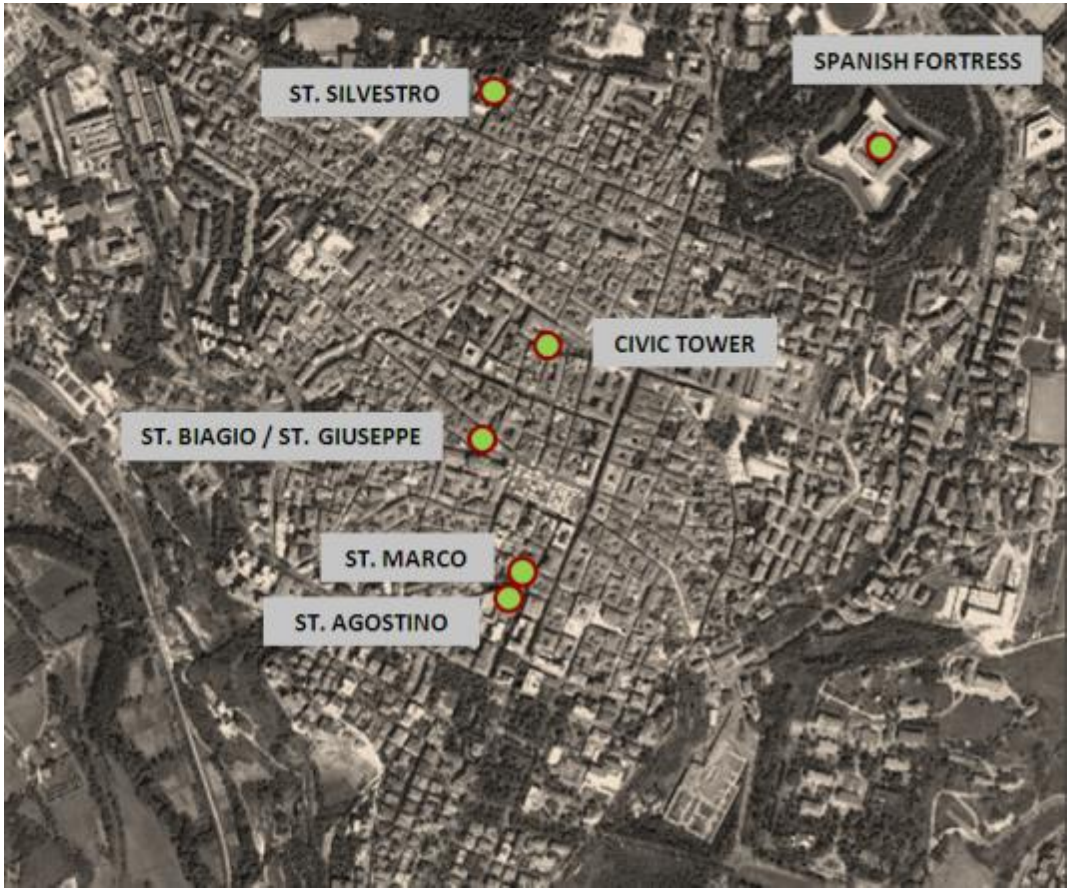
Presence of an active deterioration/damaging process

PZ 02

Reversible deformations of the crack strictly related to seasonal thermal cycles.

No active damage

iii. L'AQUILA CASE STUDIES: SHM FOR POST-EARTHQUAKE CONTROLS

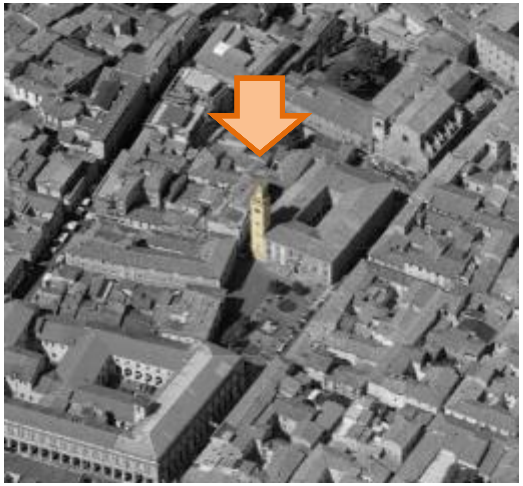
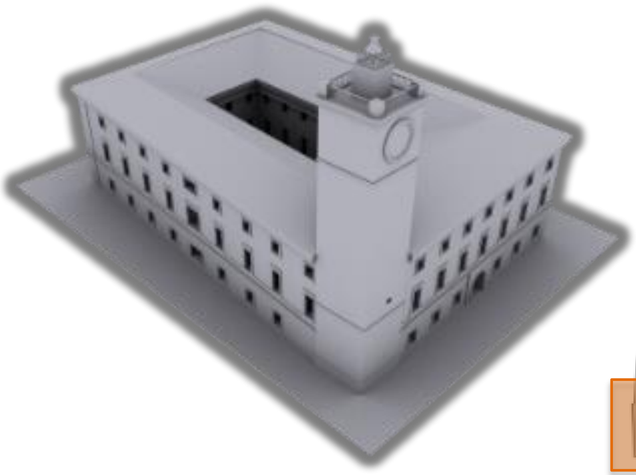
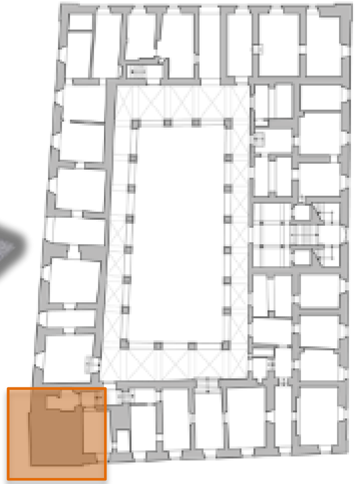


L'AQUILA SHM NETWORK (UNIVERSITY OF PADOVA & NAGOYA UNIVERSITY - JAPAN)

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)

CIVIC TOWER


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 coinceived as an isolated element
- 1294: construction of 'Margherita' palace
- 1349, 1461 and 1703: strong earthquakes induced several damages/collapses

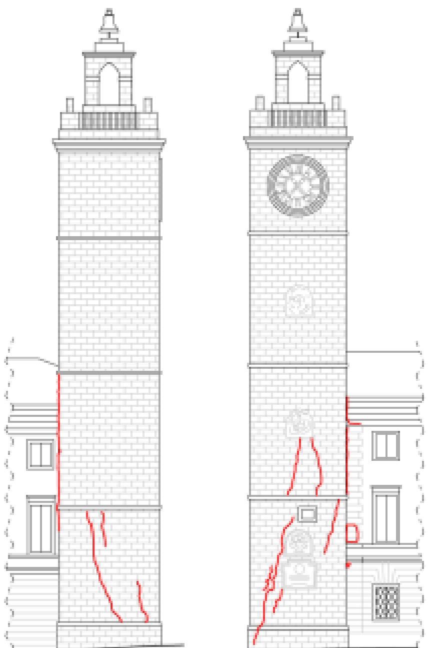
CIVIC TOWER: 6 APRIL 2009 EARTHQUAKE

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

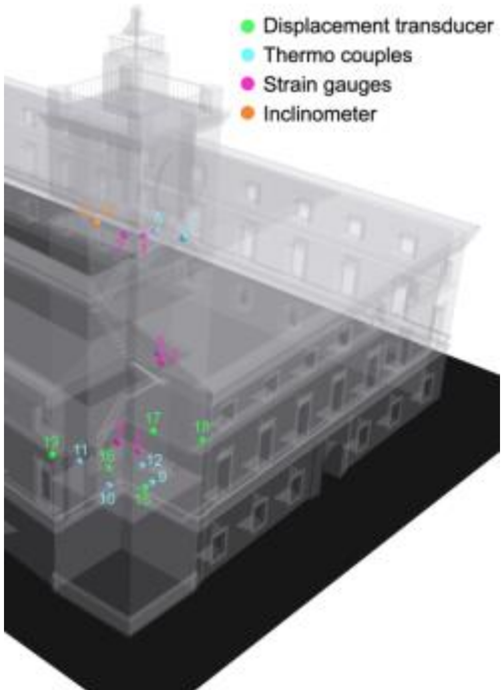
PROVISIONAL INTERVENTIONS:

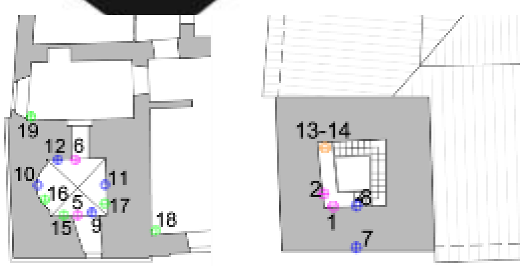
- Confinement system of the tower (steel beams, ties and timber frames)
- Improvement of the tower-palace connection
- Propping system of the palace's perimeter walls to prevent out-of-plane overturning


SOUTH FAÇADE EAST FAÇADE

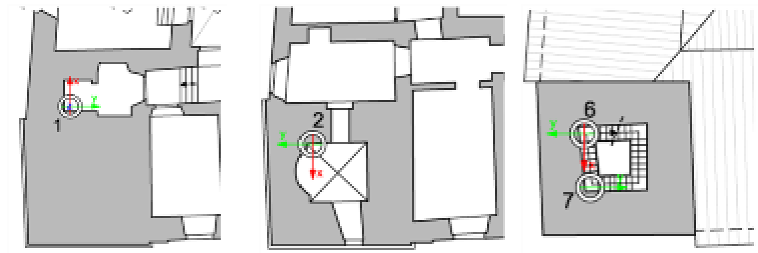
Civic Tower: the monitoring system

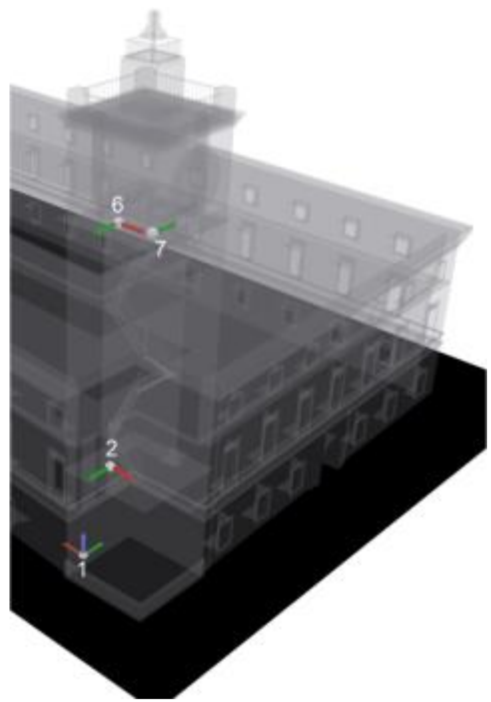
Static system





Dynamic system





Dynamic Monitoring

8 single-axis accelerometers

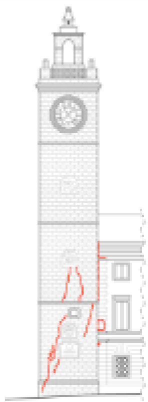
Static Monitoring

- 5 Displacement transducers
- 6 Strain gauges
- 1 Inclinometer

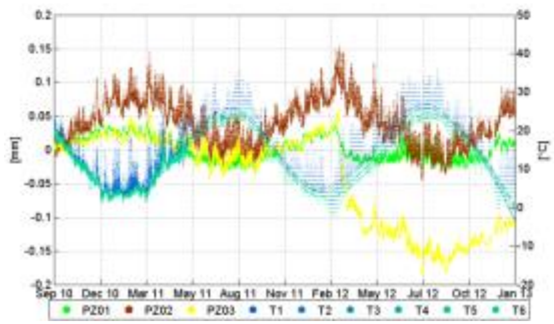
Environmental Monitoring

- 6 Thermo couples

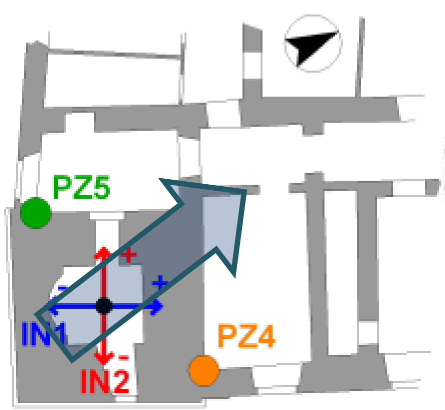
CIVIC TOWER: STATIC MONITORING RESULTS

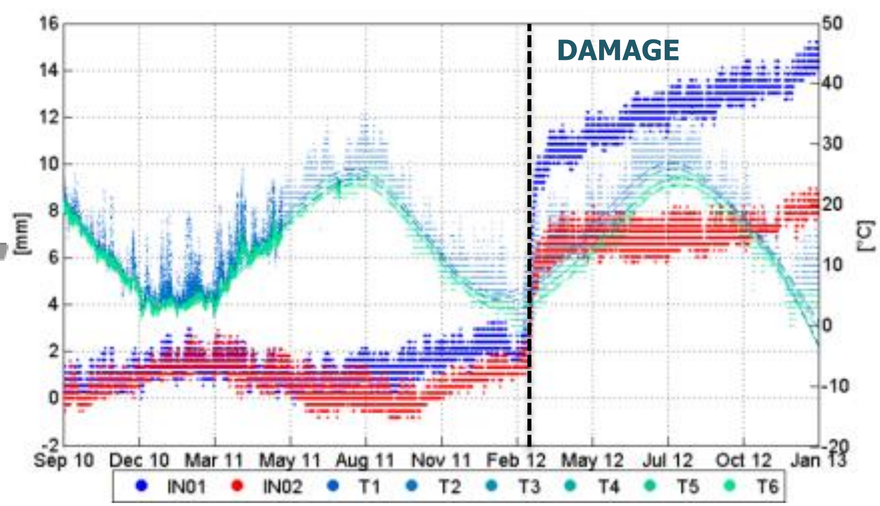


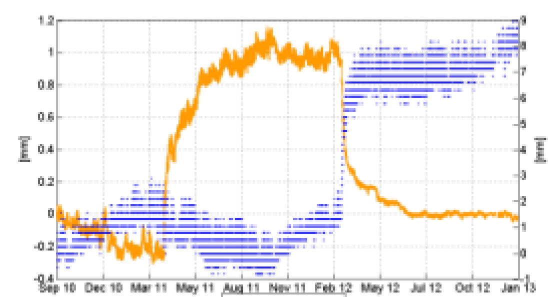
During the first 1,5 years of monitoring the crack pattern of the tower was kept rather stable



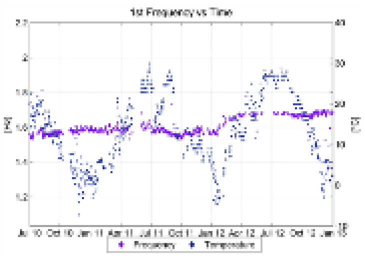
Starting from February 2012 the equilibrium conditions of the tower underwent a significant change due to a slight rotation/displacement of the tower toward the palace

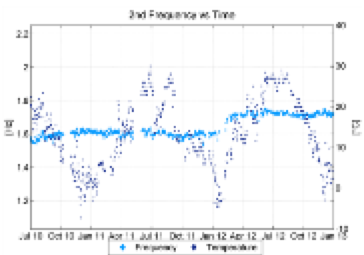


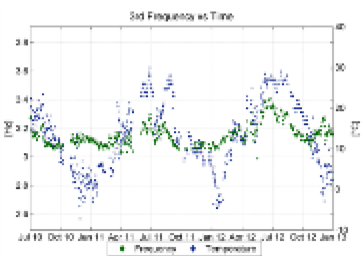


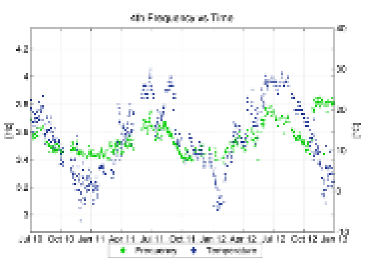


CIVIC TOWER: DAMAGE DETECTION









- 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

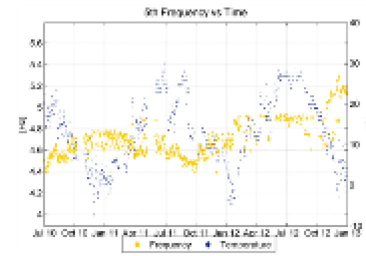
Mode	f_{max} [Hz]	f_{min} [Hz]	f_{mean} [Hz]	f_{change} [%]	f_{std} [Hz]	f_{cv} [%]
1	1,701	1,533	1,604	10,92	0,047	2,93
2	1,752	1,531	1,642	14,44	0,060	3,64
3	3,410	2,988	3,150	14,09	0,076	2,42
4	3,849	3,377	3,558	14,00	0,118	3,32
5	5,291	4,391	4,692	20,48	0,173	3,69
6	5,989	5,328	5,566	12,41	0,152	2,73
7	7,251	5,786	6,305	25,32	0,232	3,68

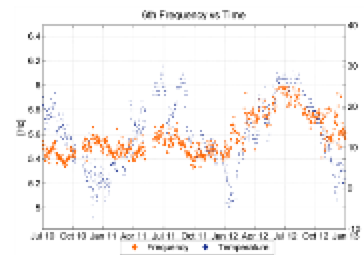
CORRELATION ANALYSIS

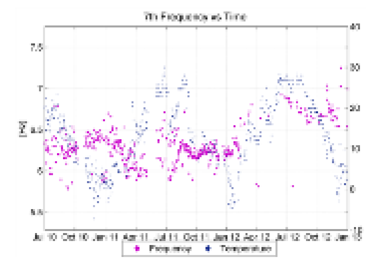
CORRELATION COEFFICIENTS							
	$f1$	$f2$	$f3$	$f4$	$f5$	$f6$	$f7$
$T1$	**0,23**	0,20	**0,50**	**0,84**	0,41	**0,13**	0,14
$T2$	0,15	0,27	0,49	0,81	0,48	0,10	0,14
$T3$	0,05	0,35	0,44	0,76	0,54	0,04	0,14
$T4$	0,04	0,35	0,44	0,75	0,54	0,04	0,13
$T5$	0,03	**0,36**	0,43	0,75	**0,55**	0,04	0,13
$T6$	0,09	0,33	0,46	0,78	0,53	0,05	**0,15**

ARX MODELS SELCTION BASED ON QUALITY CRITERIA

Mode	ARX models						Static regression models					
	n_a	n_b	n_k	λ_0	FPE	R^2	n_a	n_b	n_k	λ_0	FPE	R^2
1	7	10	0	0,0001	0,0001	0,52	0	1	0	0,0003	0,0003	0,23
2	6	10	0	0,0001	0,0001	0,38	0	1	0	0,0002	0,0002	0,36
3	5	9	0	0,0004	0,0004	0,54	0	1	0	0,0018	0,0018	0,50
4	9	10	0	0,0004	0,0005	0,85	0	1	0	0,0016	0,0016	0,84
5	0	10	0	0,0051	0,0054	0,54	0	1	0	0,0055	0,0056	0,55

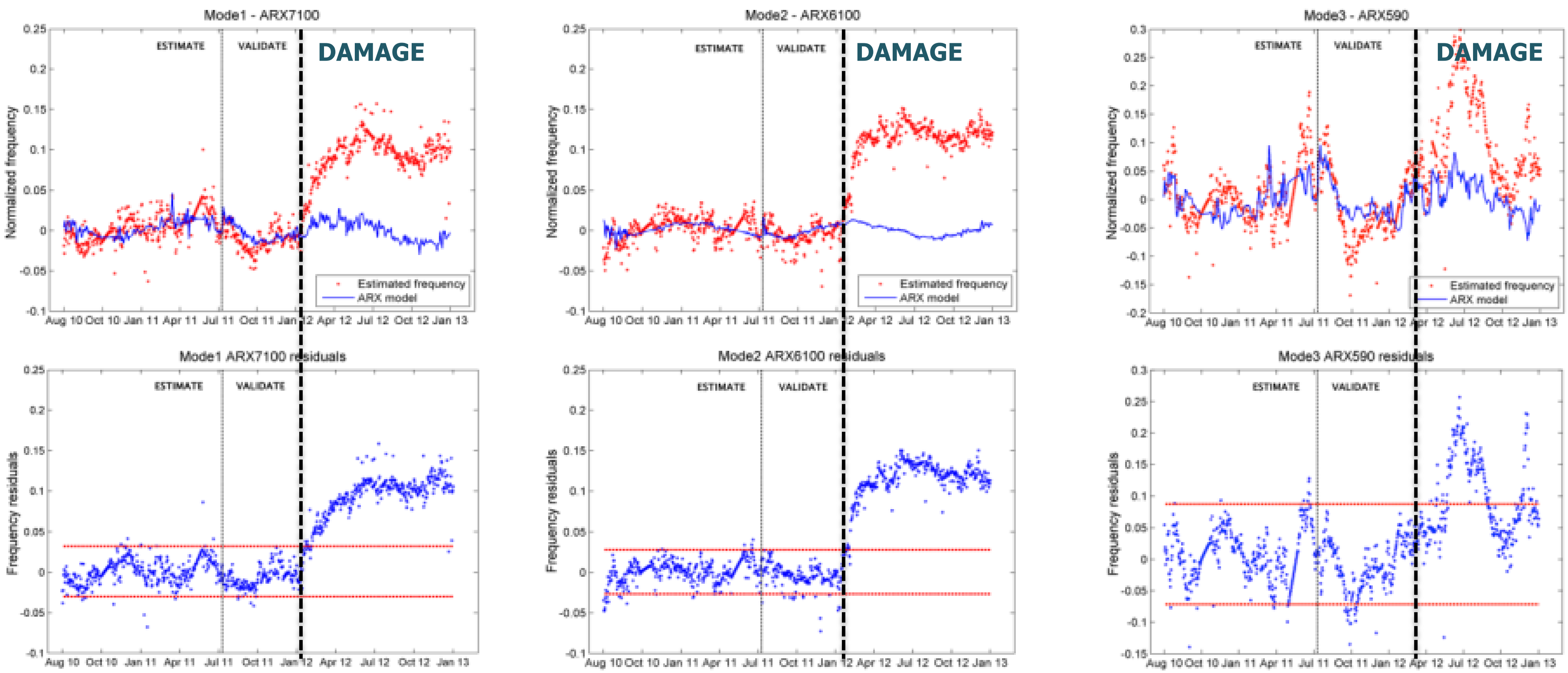






RESIDUAL ANALYSIS AND DAMAGE DETECTION

MODE 1: 1st bending E-W | MODE 2: 1st bending N-S | MODE 3: 2nd bending N-S

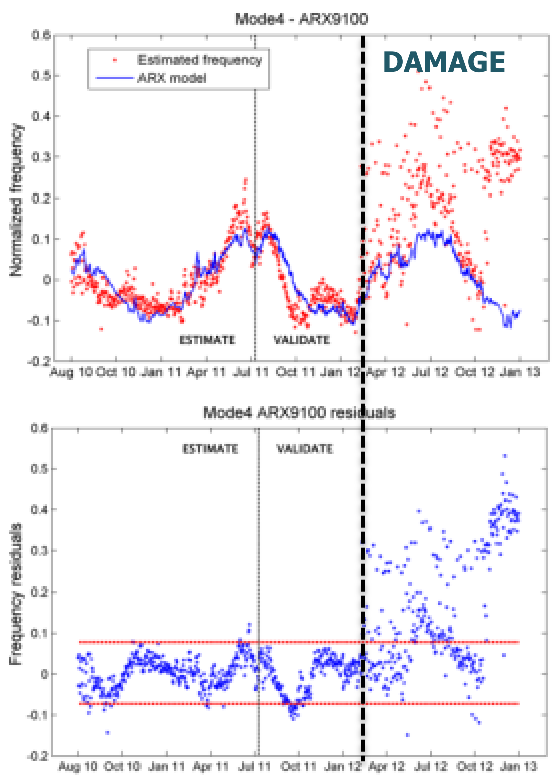


CONCLUSIONS

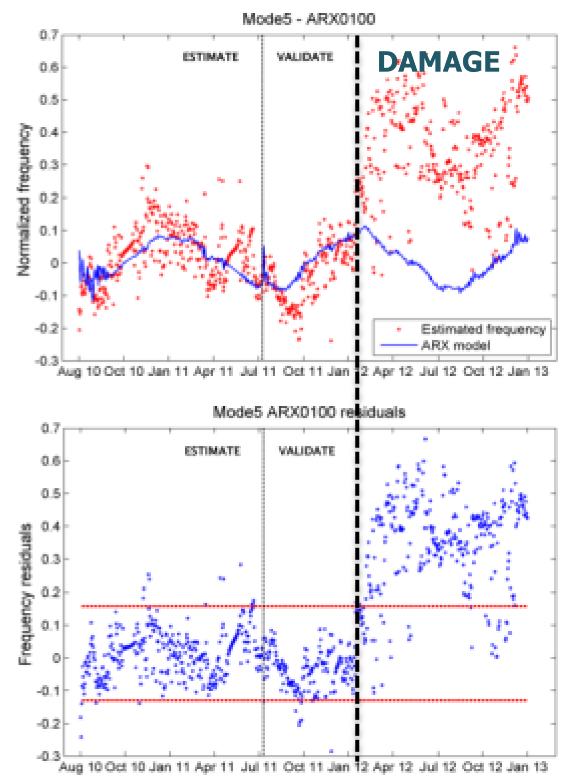
- Until Feb 2012 → damage is stable since the residuals are always included within confidence intervals
- From Feb 2012 → the equilibrium condition of the tower changed due to a displacement of the tower
- It was possible to detect damage/modification of the structural layout demonstrated by an increment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

RESIDUAL ANALYSIS AND DAMAGE DETECTION

MODE 4: 2nd bending E-W



MODE 5: 1st torsion



CONCLUSIONS

- Until Feb 2012 → damage is stable since the residuals are always included within confidence intervals
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- It was possible to detect damage/modification of the structural layout demonstrated by an increment of frequencies

THE TOWER OF DAVID

The Tower of David is a historical and archeological asset located near the Jaffa Gate entrance to the Old City of Jerusalem. Built to strengthen a strategically weak point in the Old City's defenses, the citadel that stands today has ancient foundations and was constructed during the 2nd century BC and subsequently destroyed and rebuilt by, in succession, the Christian, Muslim, Mamluk, and Ottoman conquerors of Jerusalem. It contains important archaeological finds dating back 2,700 years

Tower of David in late 1920s

The citadel compound includes archeological findings attesting to Jerusalem's long and eventful history: remains of a quarry from the First Temple period; a segment of the wall surrounding Hasmonean Jerusalem (the first wall); remains of monumental steps, probably from Herod's palace which was located nerby; remains of a fortress that stood in this location during the rule of the Ummayid dynasty (7th and 8th century CE) and more

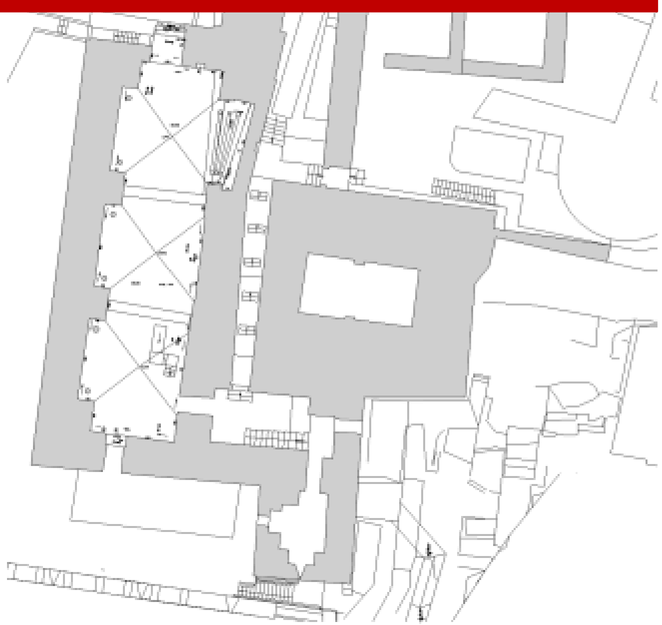
MASTERPLAN

MASTERPLAN

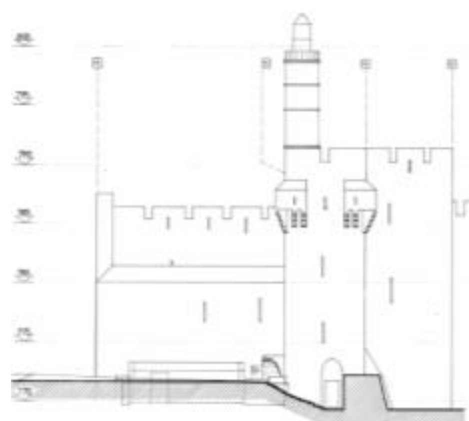
GEOMETRIC SURVEY

LEVEL 2 (+10 m)

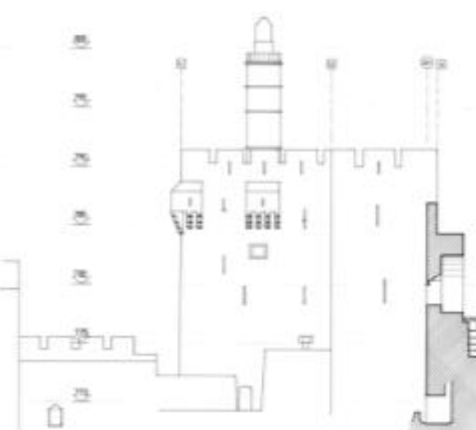
LEVEL 1 (+5 m)



SOUTH ELEVATION

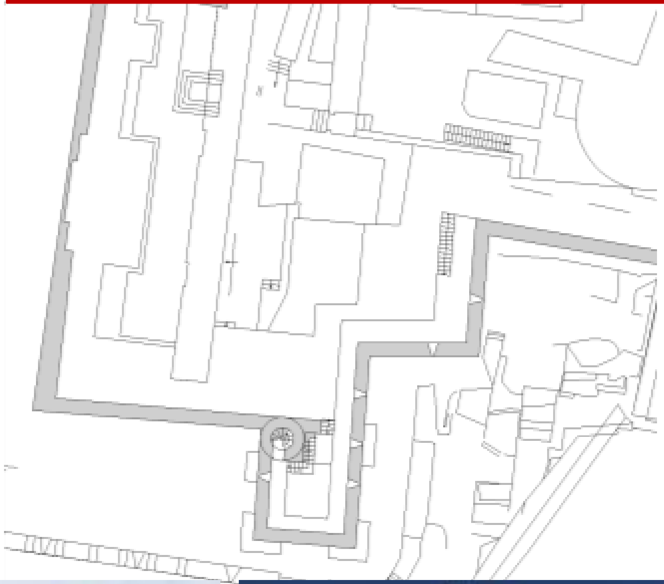


EAST ELEVATION



GEOMETRIC SURVEY

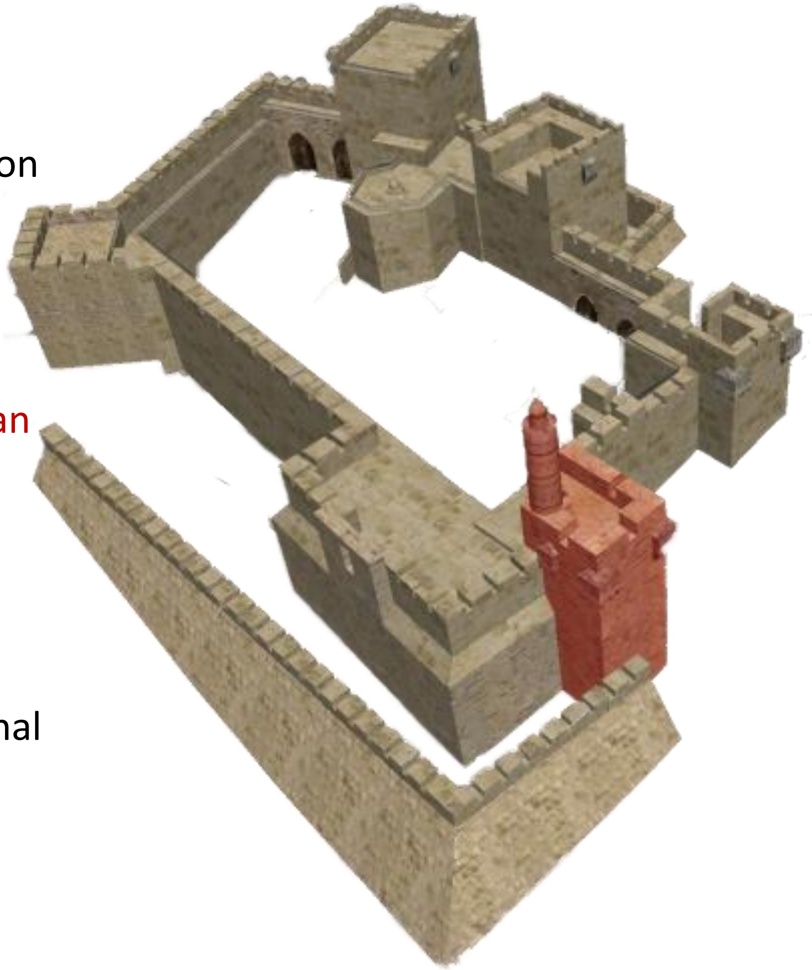
LEVEL 4 (+20 m)



LEVEL 3 (+17 m)

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/expoloitation of the monument
- SHM in the framework of a maintenance/conservation plan of the Tower of David 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



DESIGN AND INSTALLATION OF A STATIC AND DYNAMIC STRUCTURAL HEALTH MONITORING SYSTEM

NOVEMBER 2013

PRELIMINARY INSPECTIONS

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:

- Severe damages and cracks on the top of the minaret
- Cracks at the basement of the tower

WEST ELEVATION

PRELIMINARY INSPECTIONS

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:

- Severe damages and cracks on the top of the minaret
- Cracks at the basement of the tower

SOUTH ELEVATION

MONITROING SYSTEM

DYNAMIC

- **8 Single-axis piezoelectric accelerometers**
  Sensitivity: 1019.4 mV/(m/s^2)
  Frequency range (± 10 %): 0.1÷2000 Hz
  Resolution (da 10,000 Hz): 0.00008 m/s^2
  Working temperature: -45÷82 °C

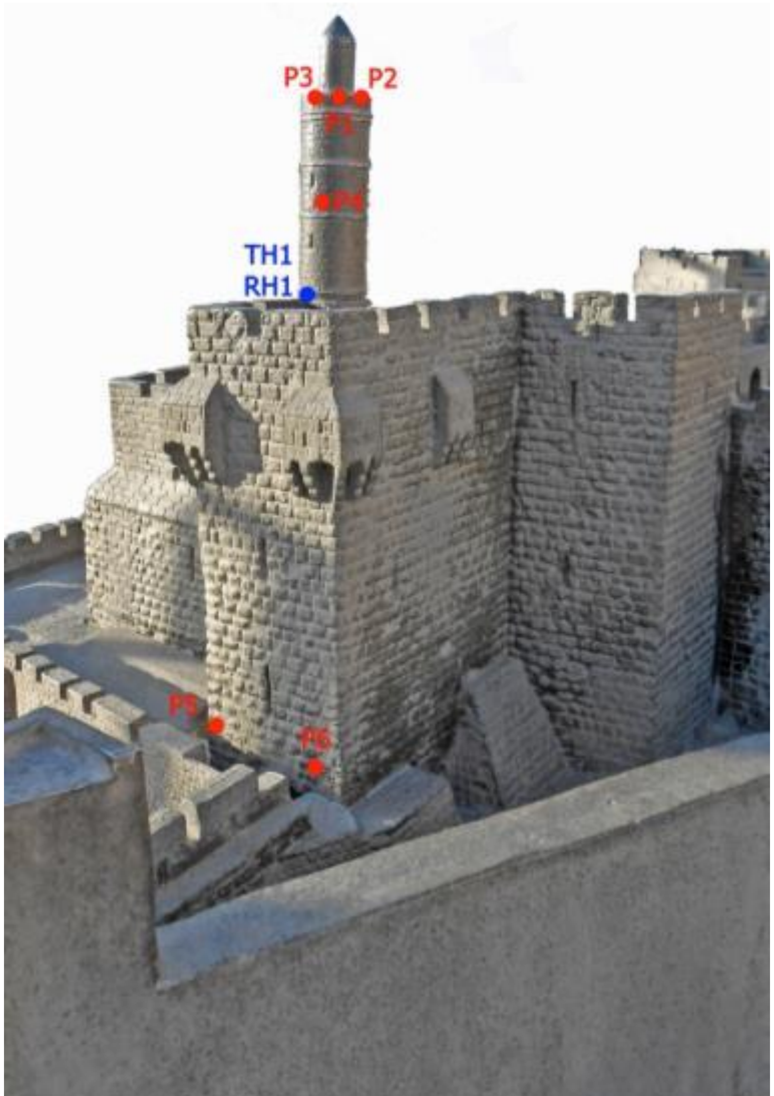
STATIC

- **6 Displacement transducers**
  Voltage: 0÷10 V
  Range of measurement: 10 cm
  Hysteresis: < 0.01 mm
  Working temerature: -30÷100 °C

ENVIRONMENTAL

- **1 Integrated sensor temperature and relative humidity**
  Voltage: 0÷10 V
  Precision: +/- 2 % RH
  +/- 0.2 °C
  Measure range: 0÷100% RH
  - 20/0÷50 °C

STATIC SYSTEM



P1

P2

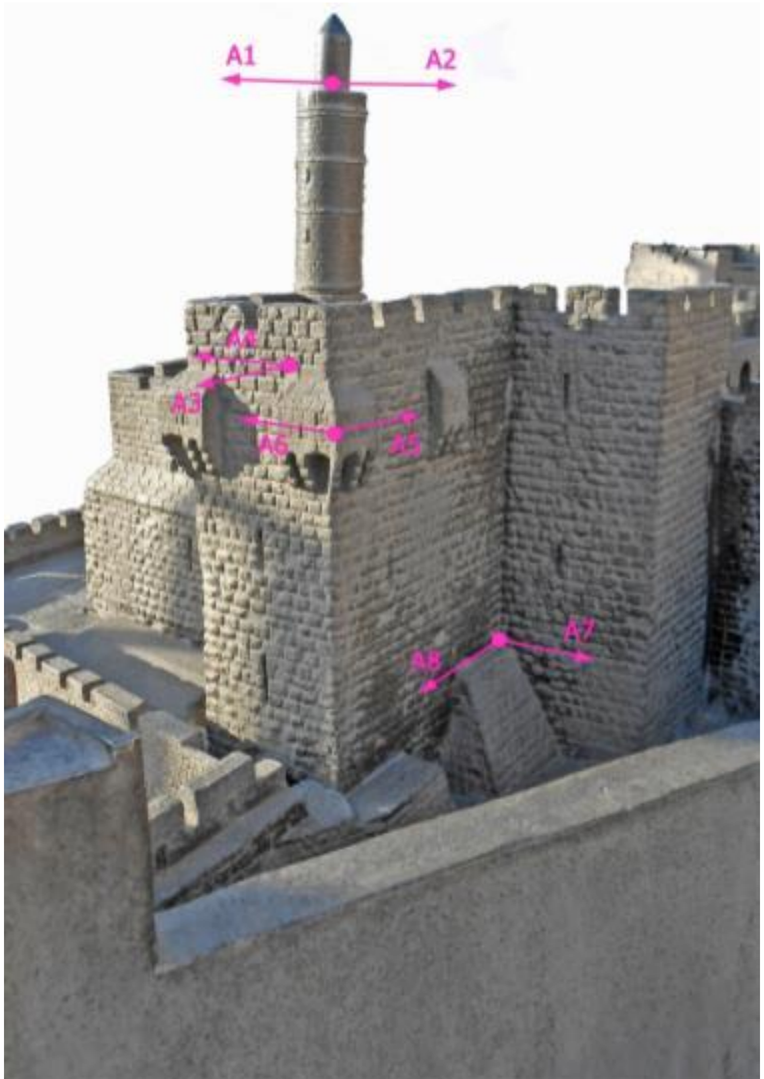
P3

P4

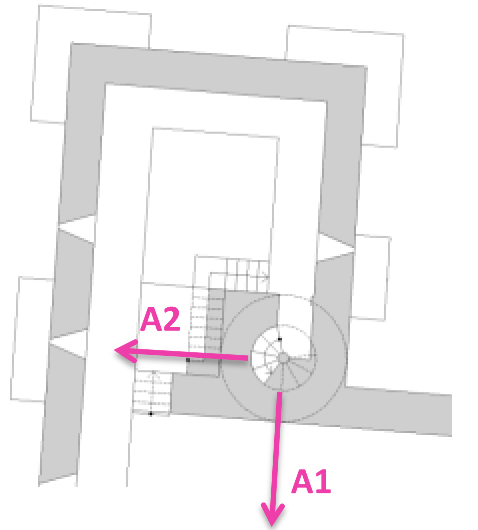
P5

P6

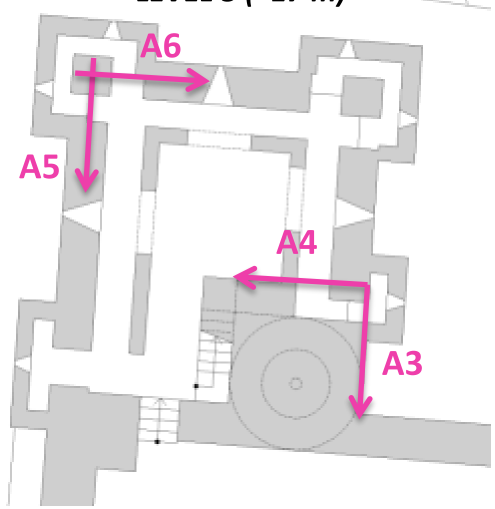
DYNAMIC SYSTEM



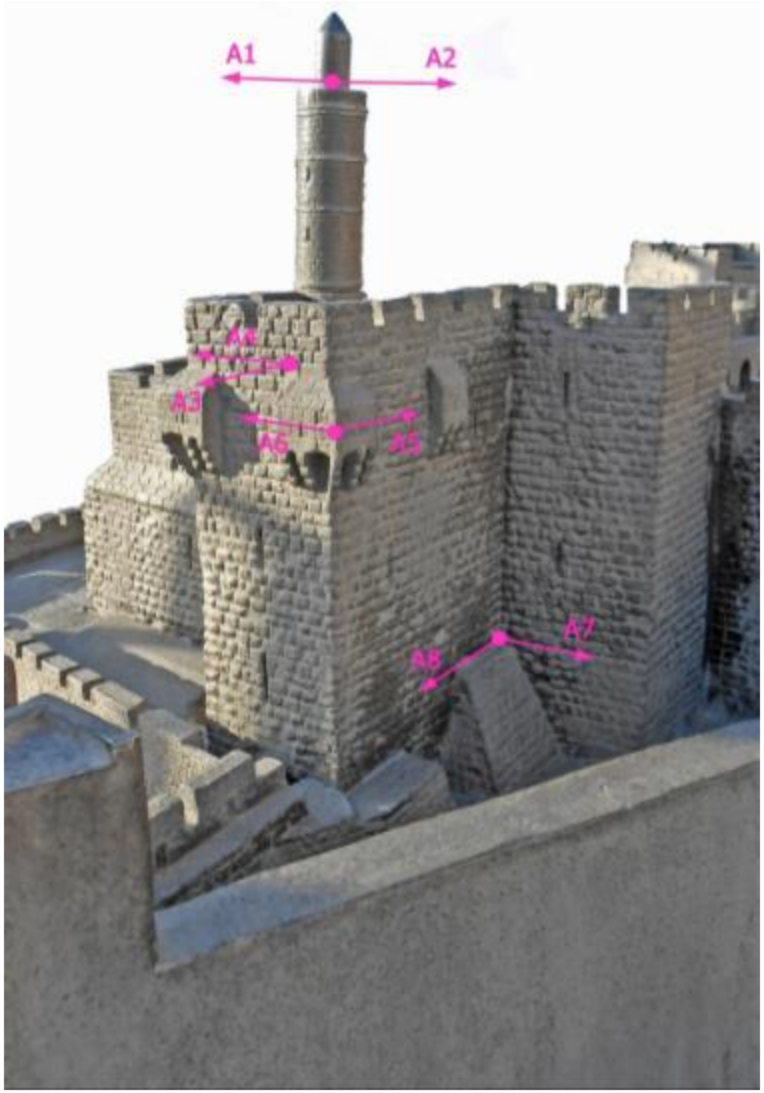
LEVEL 5 (+30 m)



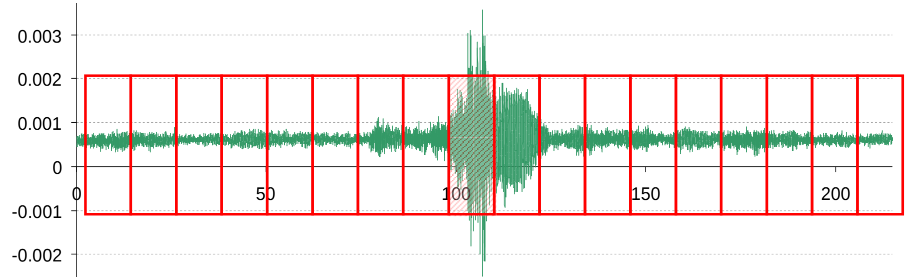
LEVEL 3 (+17 m)

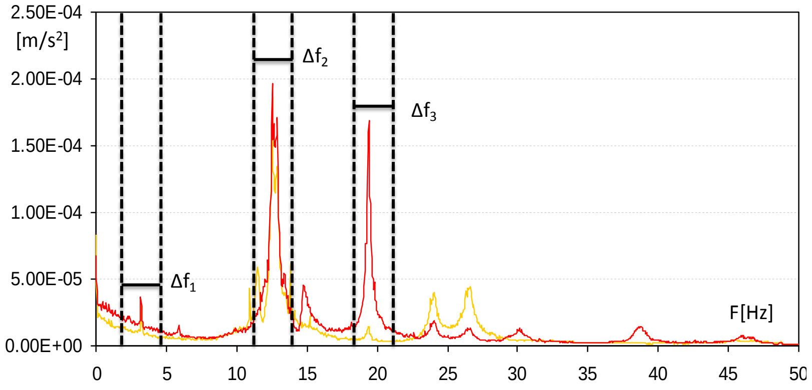


DYNAMIC SYSTEM

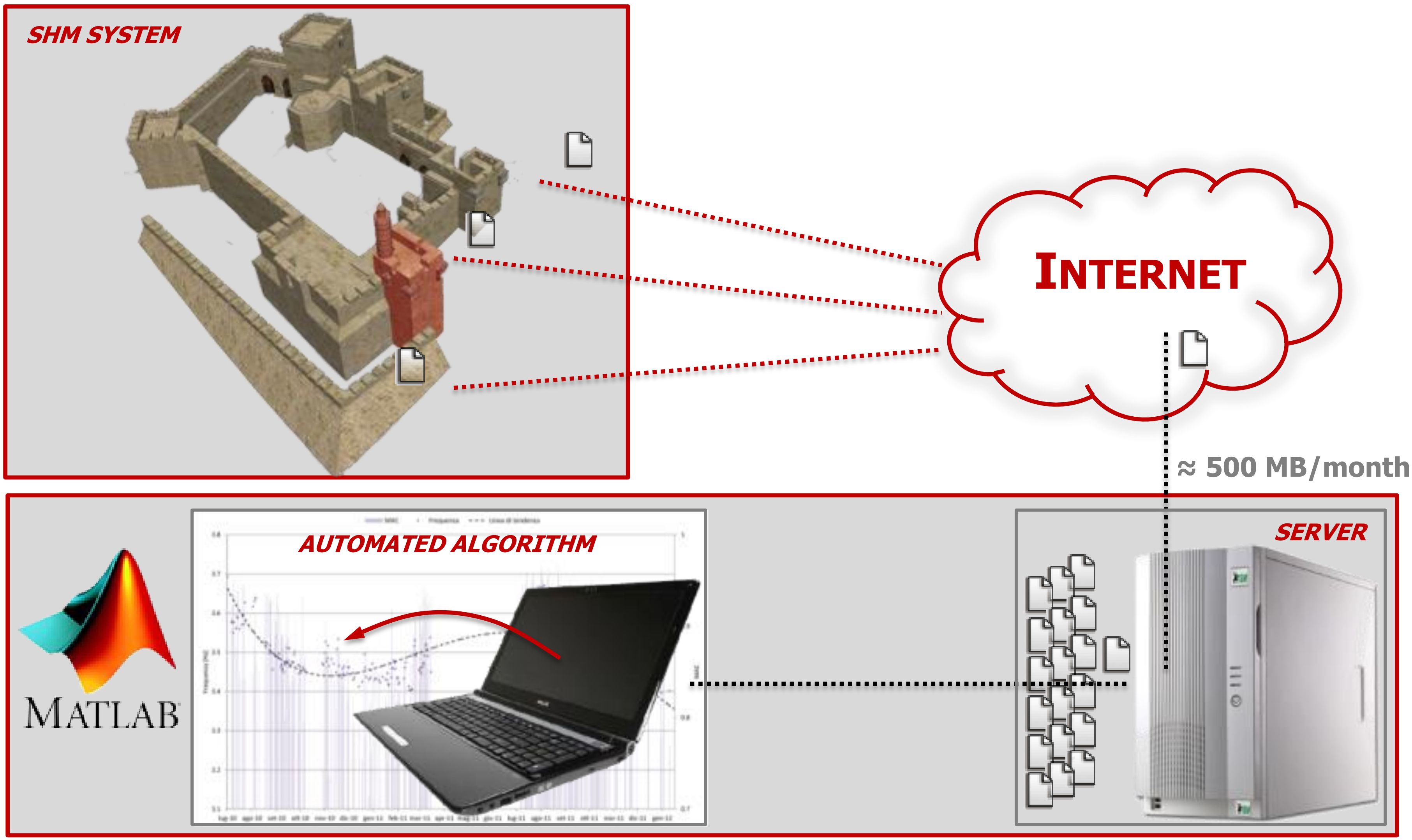


Dynamic data are being collected both at fixed time intervals ("long" acquisition, corresponding to 131'072 points, or to 21'51'' of record at a sampling frequency of 100 SPS, each 12 hours) to allow successive dynamic identification of the structure with different environmental conditions, and on a trigger basis (shorter records, 3'35'' at a sampling frequency of 100 SPS), when the signal, on one of the acceleration channels, gets over the predefined threshold



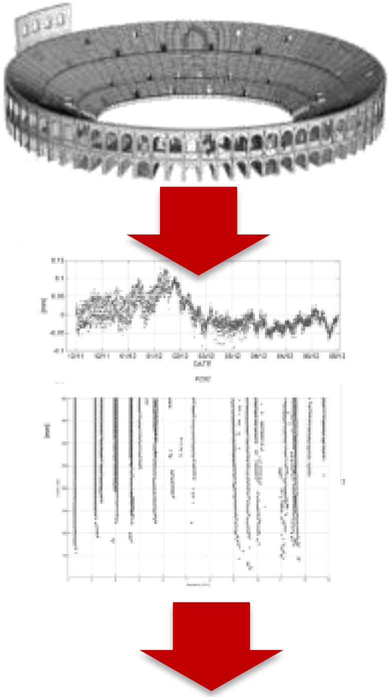


AUTOMATED DATA PROCESSING



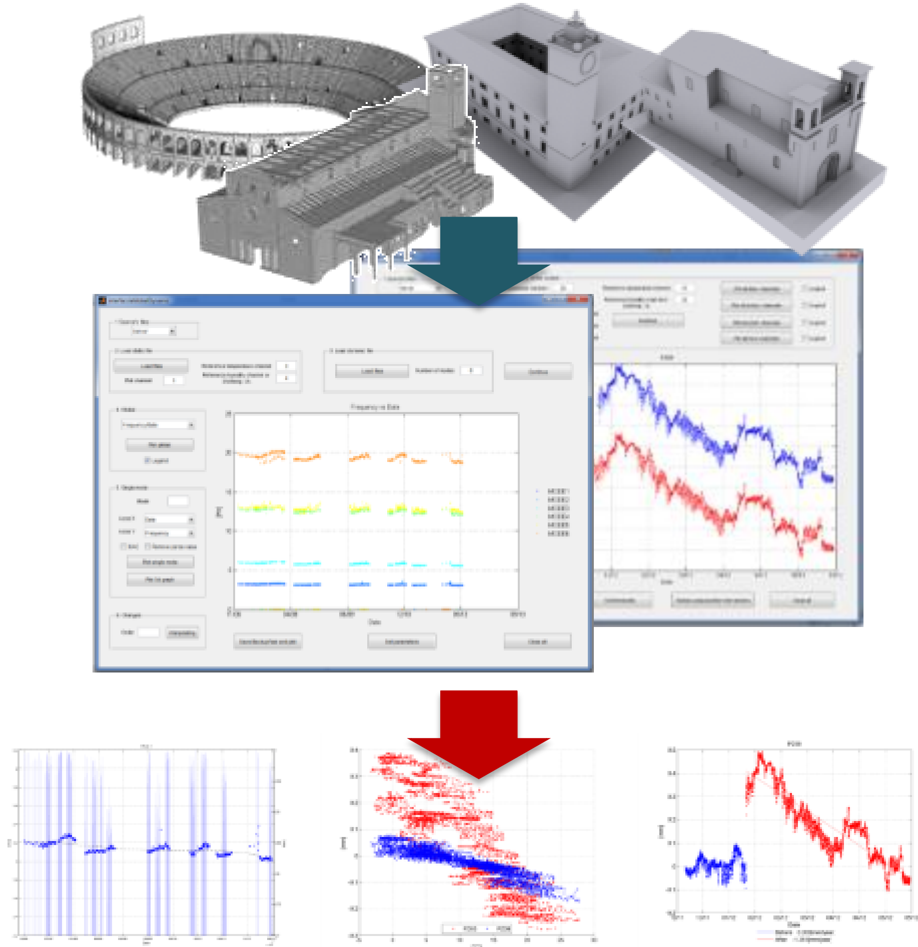
AUTOMATED DATA PROCESSING

Automatic Subroutine (no user-interaction)



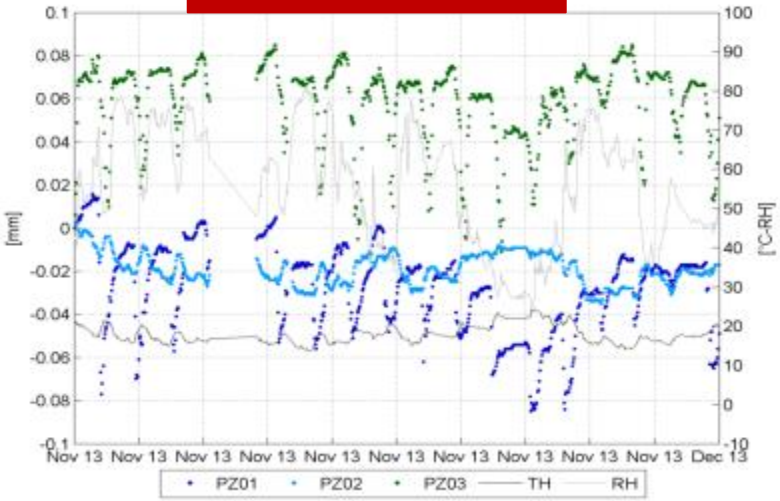
- Early warning messages
- Automatic plot of results
- Detection of system or sensor malfunction

Graphical User Interface (GUI)

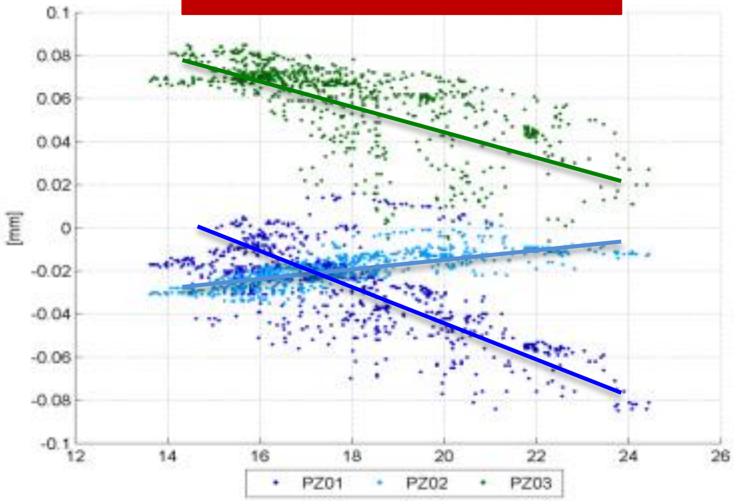


MONITORING RESULTS

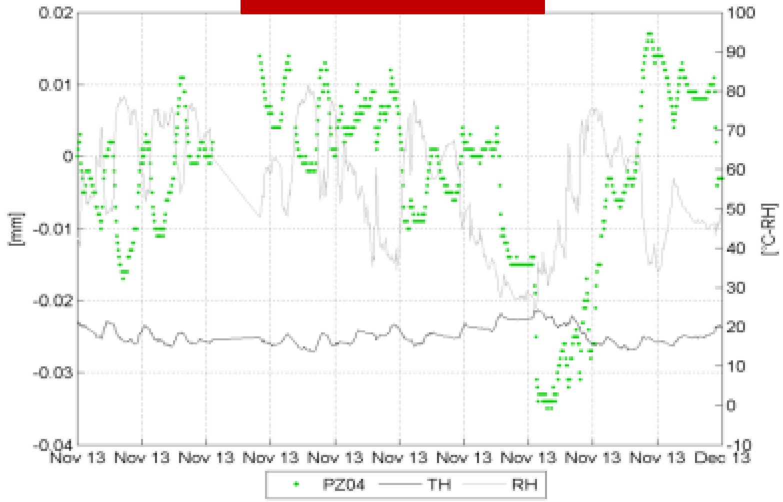
P1-P2-P3 vs. TIME



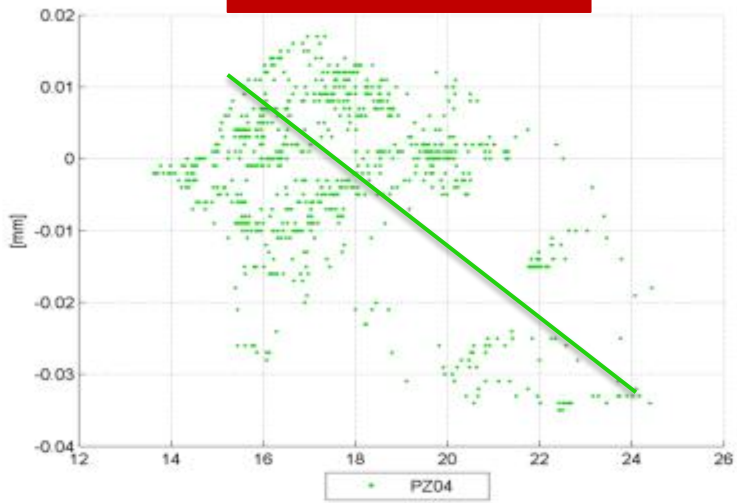
P1-P2-P3 vs. TEMPERATURE



P4 vs. TIME

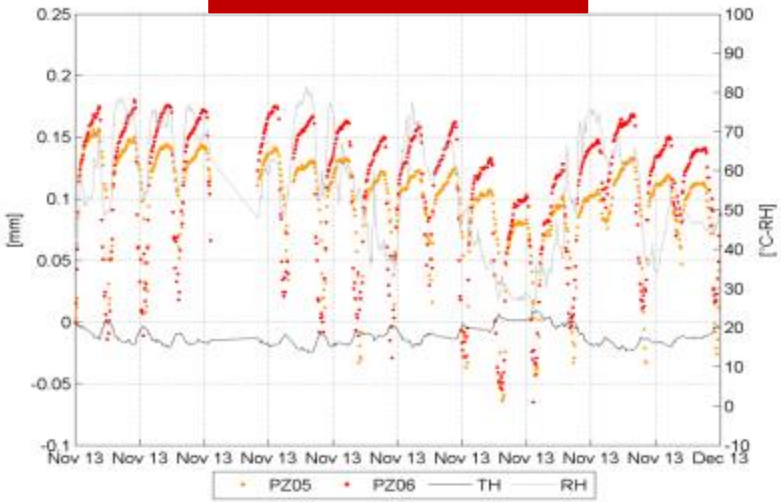


P4 vs. TEMPERATURE

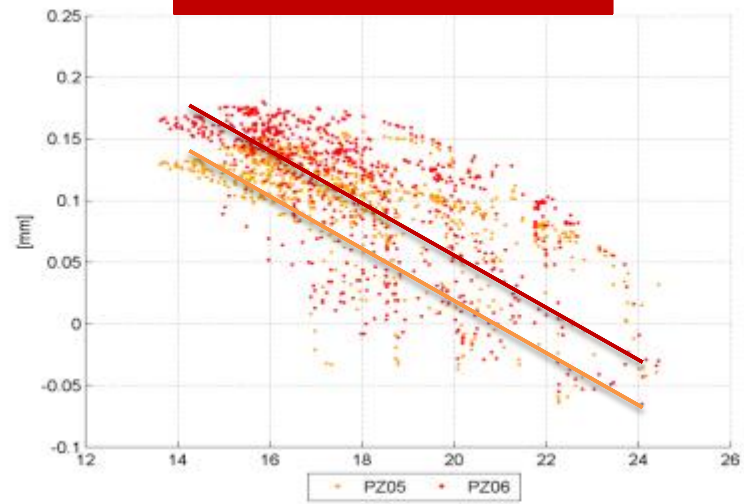


MONITORING RESULTS

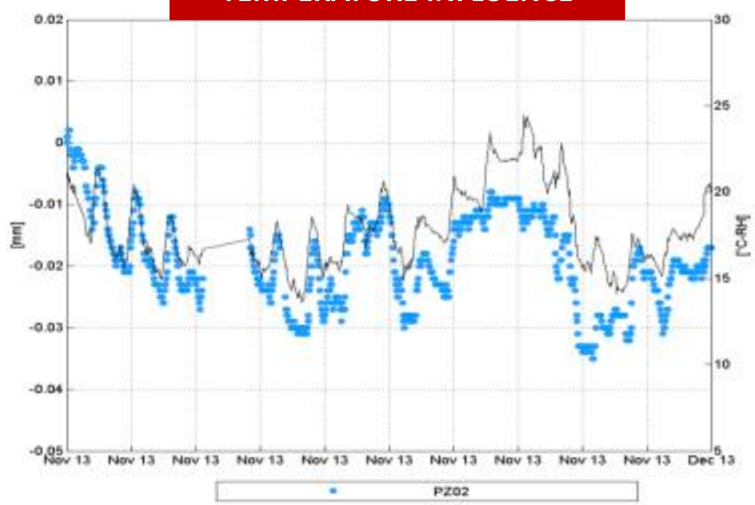
P5-P6 vs. TIME



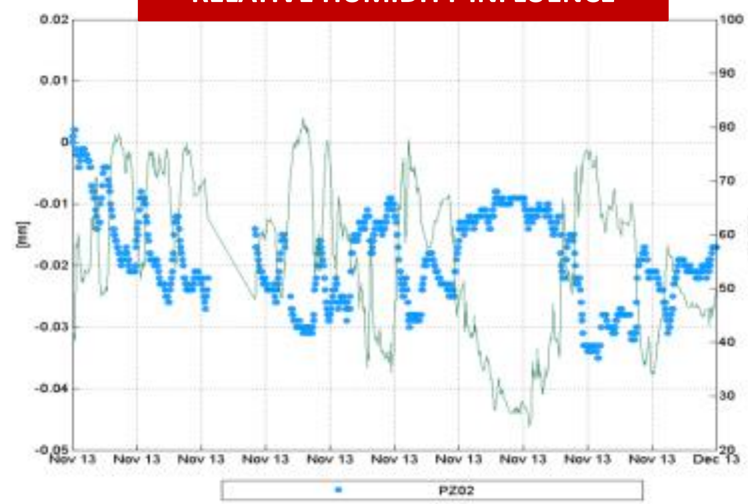
P5-P6 vs. TEMPERATURE



TEMPERATURE INFLUENCE

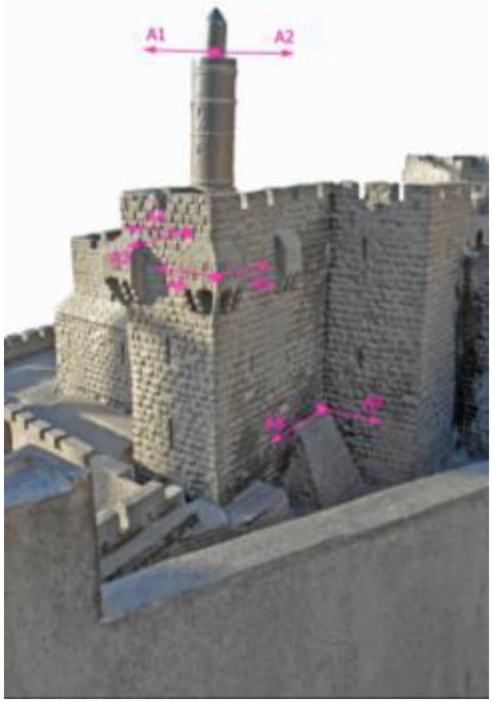


RELATIVE HUMIDITY INFLUENCE



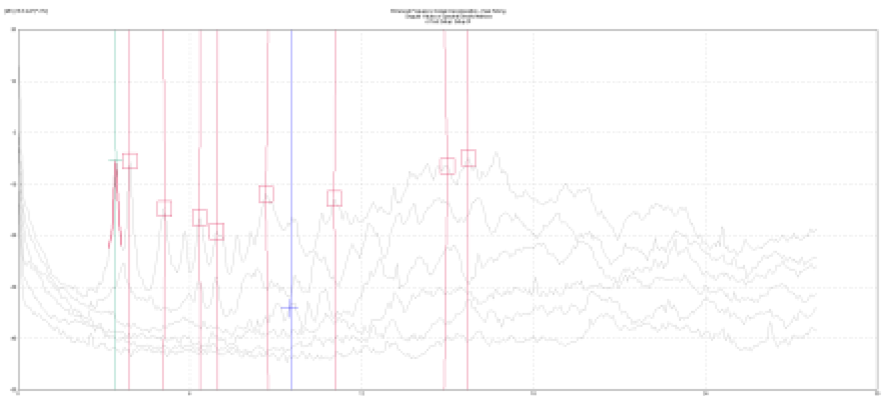
MONITORING RESULTS: OPERATIONAL MODAL ANALYSIS

- Identification of the dynamic behaviour of the Tower
- Exploitation of the results for model updating
- Comparison of results using different OMA techniques
- SF 100 Hz; 131’072 points; record lenght: 21’51’’ sec
- System identification: decimation; segment length 2048 points, 66.67% overlap; selected methods: FDD and EFDD



Example of recorded time history

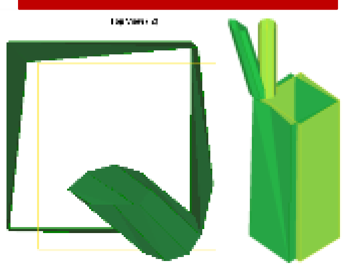
MONITORING RESULTS: OMA



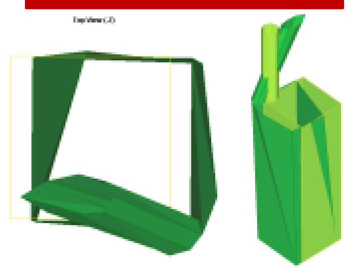
Singular values decomposition of the power spectral density matrix

MODE	FDD	EFDD		MAC	Comment
	f [Hz]	f [Hz]	ξ [%]		
1	3,42	3,41	0,97	0,99	1st bending X
2	3,90	3,91	0,92	1	1st bending Y
3	5,13	5,09	1,72	0,99	2nd bending X
4	6,35	6,36	1,47	0,98	2nd bending Y
5	6,93	6,99	1,63	0,99	3rd bending Y
6	8,64	8,73	2,48	0,99	4th bending Y
7	11,04	11,07	1,07	0,98	1st torsion
8	14,89	14,88	1,09	0,98	5th bending X
9	15,72	15,7	0,85	0,99	6th bending Y

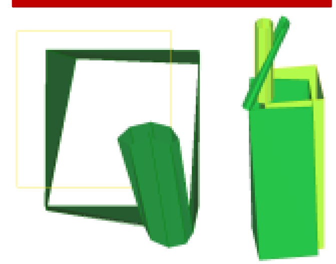
MODE 1 - 3.41 Hz



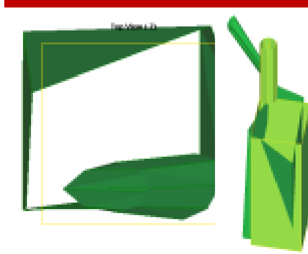
MODE 3 - 5.09 Hz

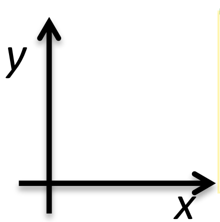


MODE 5 - 6.99 Hz

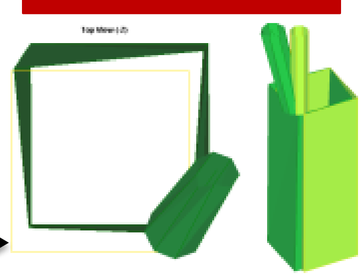


MODE 7 - 11.07 Hz

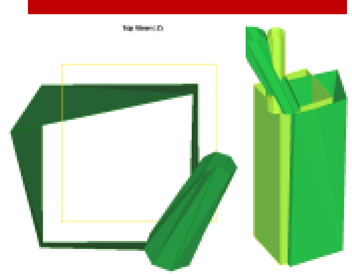




MODE 2 - 3.9 Hz

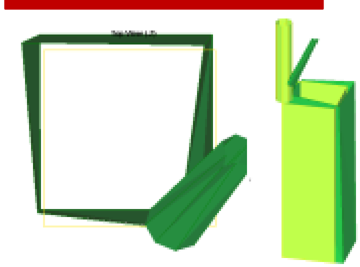


MODE 4 - 6.36 Hz



MODE 6 - 8.73 Hz

MODE 8 - 14.88 Hz



THANK YOU FOR YOUR KIND ATTENTION!

Speaker: Dr. Eng. Filippo Lorenzoni

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