ViBest_SHM: A digital data repository for SHM

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10 Dynamic Monitoring Programs

Infante D. Henrique Bridge

Braga Stadium Roof

Trezoi Bridge

Grande Ravine Bridge (Indic Ocean)

Wind Turbine

Tua Bridges

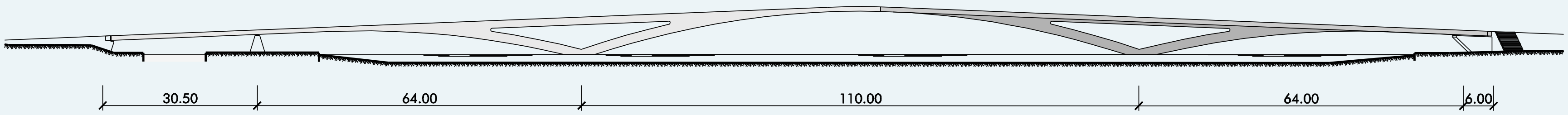
Footbridges

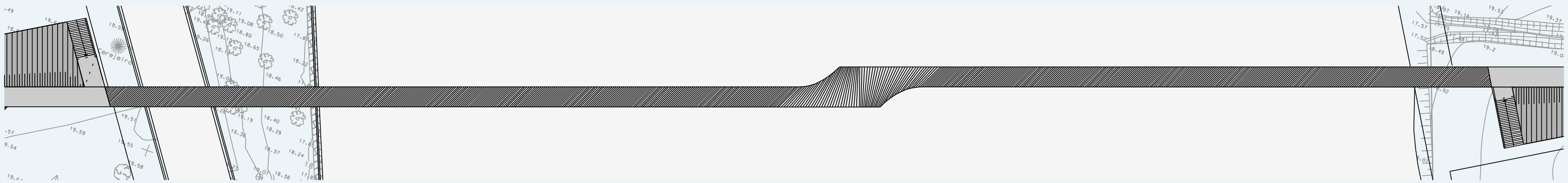
Objectives of Dynamic Monitoring

- Monitoring of **human induced vibrations** for vibration serviceability safety checking
- Monitoring of dynamic effects of **traffic loads in roadway and railway bridges** and **fatigue assessment**
- Dynamic monitoring for **damage detection in bridges**
- Dynamic monitoring of **wind effects** in large bridges and suspension roofs
- Vibration based **SHM of wind turbines**
- Vibration based **SHM of concrete arch dams**

Monitoring of human induced vibrations for vibration serviceability safety checking

- Pedro e Inês footbridge (Coimbra)





L=275m

Parabolic arch 110m span, 9m rise

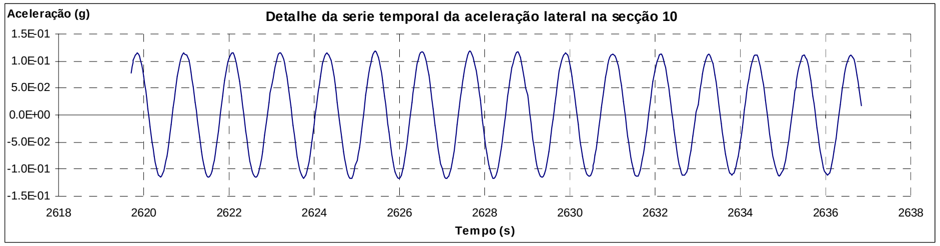
2 half-arches 64m long, asymmetric box section

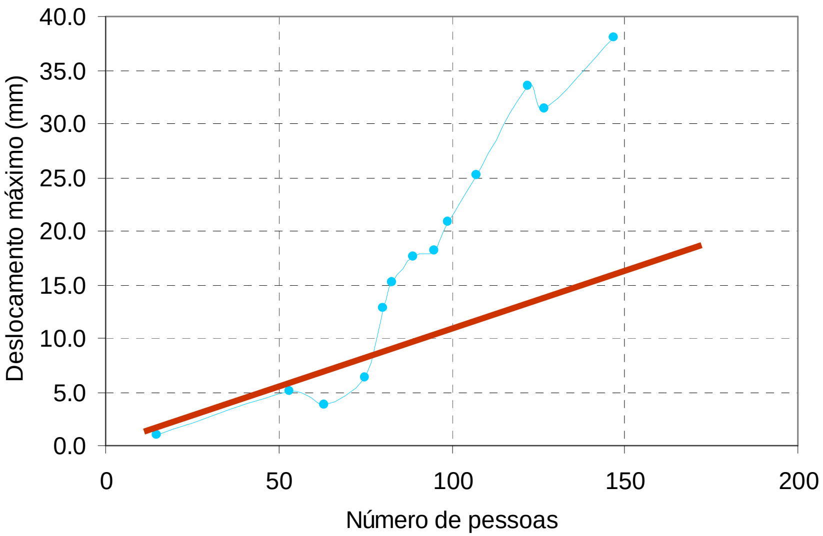
Composite deck, 4m width

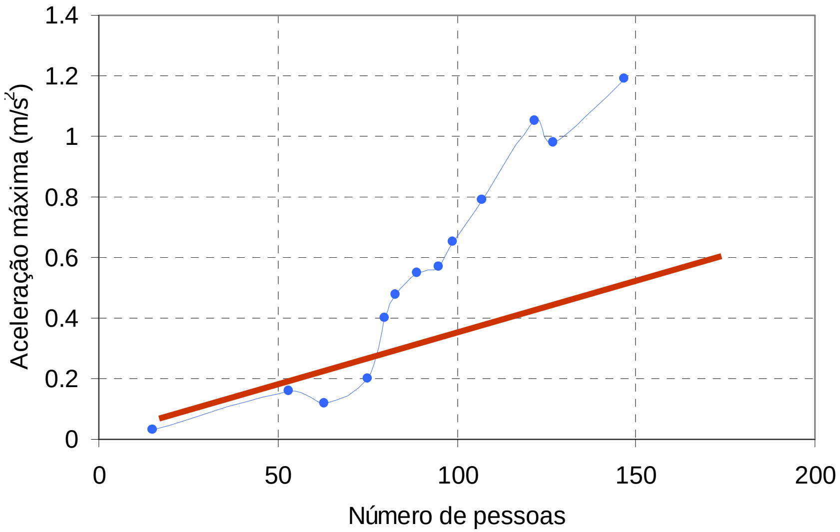
Arch foundation: massifs of 35m deep vertical piles

Dynamic tests at the end of construction
Crowd tests (excessive lateral vibrations)

- **Variation of response with number of persons on the bridge**

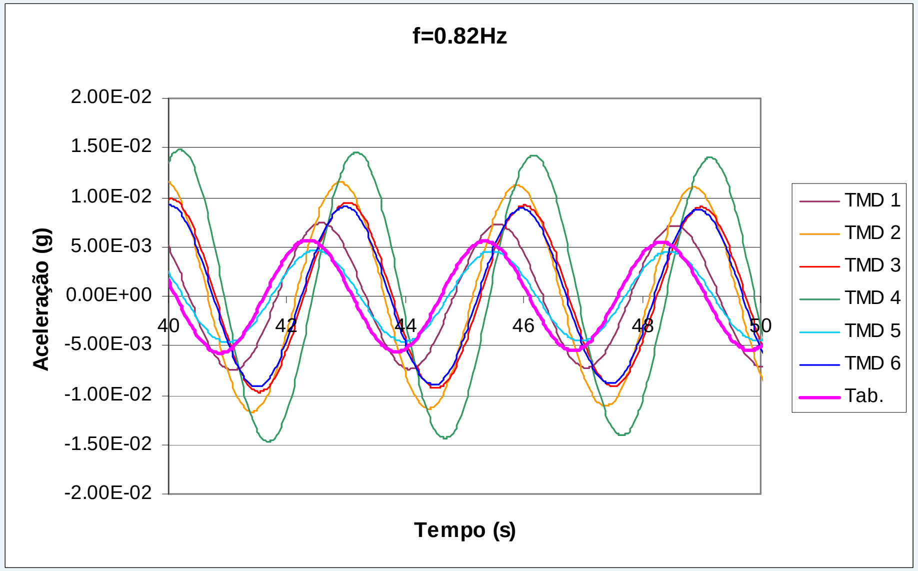






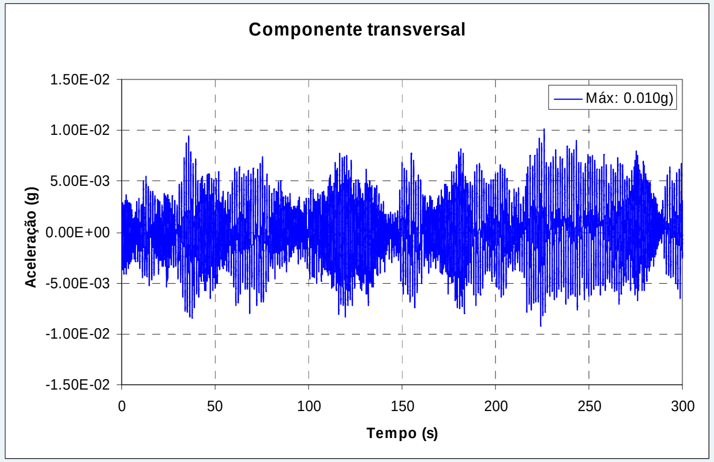
Forced vibration tests

- Evaluation of the efficiency of the TMDs

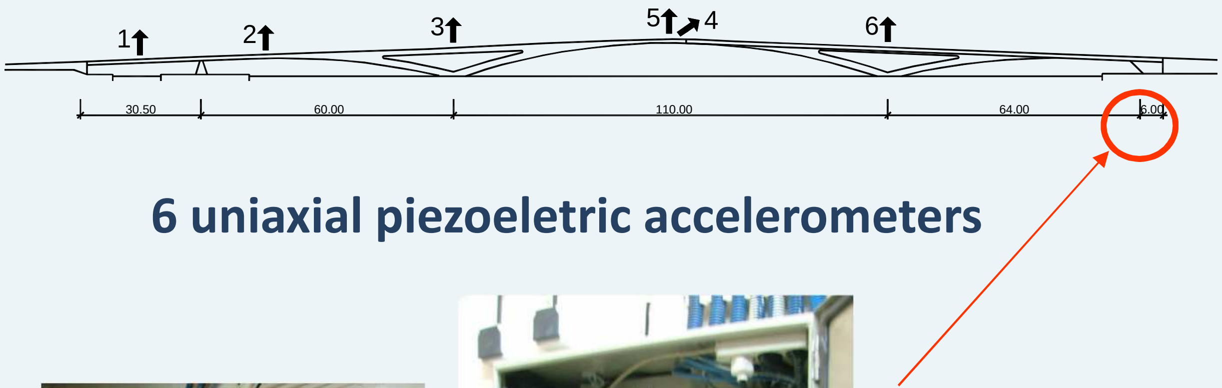


- Multiple units of the same TMD reduce global efficiency
-TMD design based on linear viscous damper is unconservative in this application

Opening day


Componente transversal
Máx: 0.010g)
1.50E-02
1.00E-02
5.00E-03
0.00E+00
-5.00E-03
-1.00E-02
-1.50E-02
Aceleração (g)
0
50
100
150
200
250
300
Tempo (s)

5-years Continuous Dynamic Monitoring



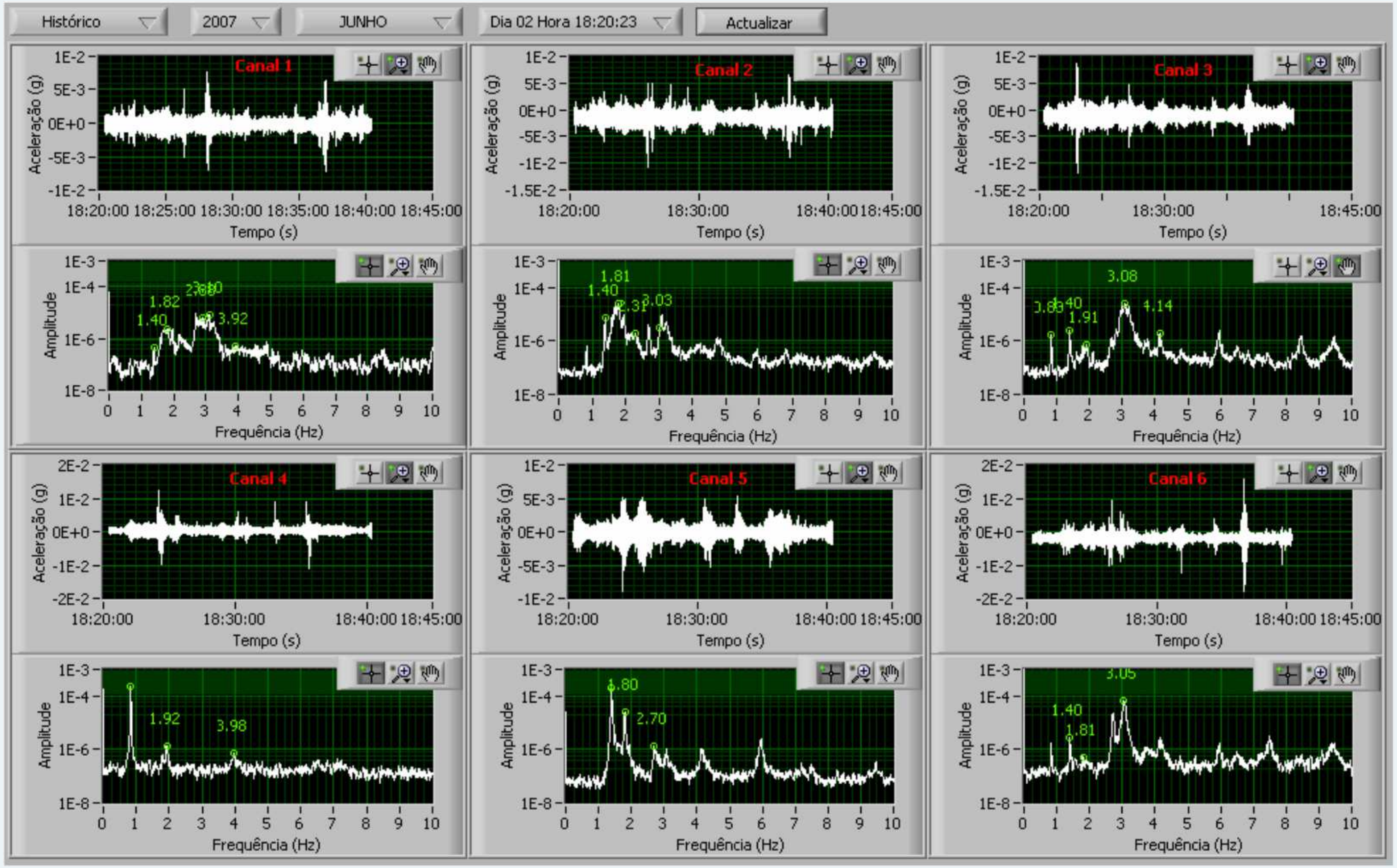
6 uniaxial piezoeletric accelerometers

Observation centre

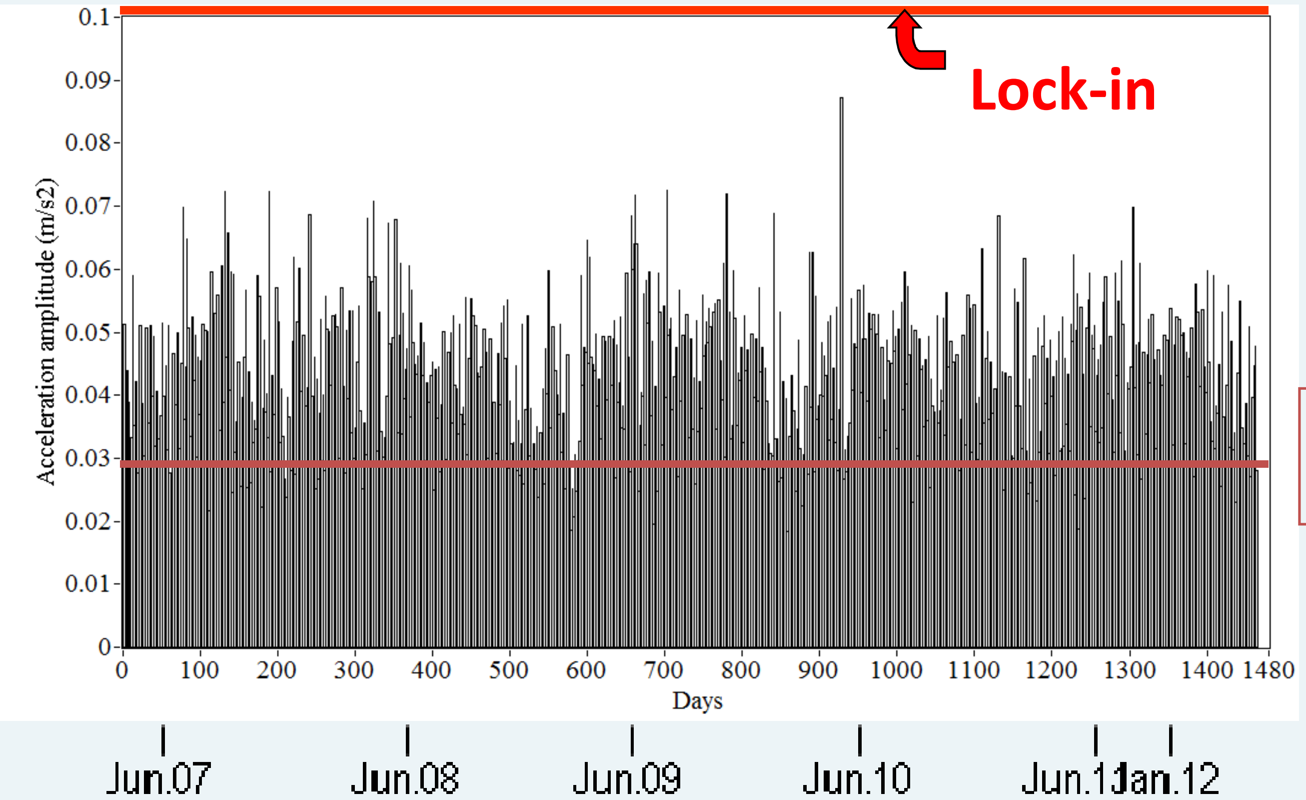
- Data acquisition from static and dynamic monitoring systems
- Data transmission

5-years Continuous Dynamic Monitoring

Website



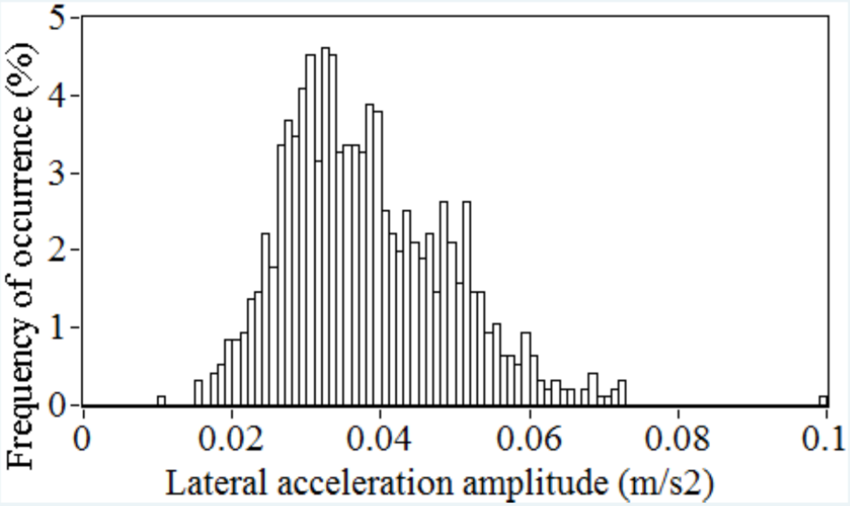
5-years Continuous Dynamic Monitoring



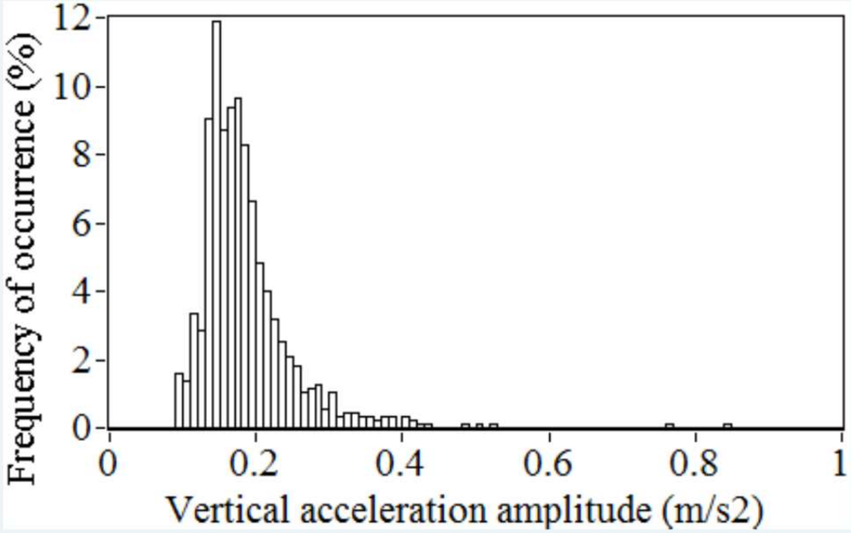
TMD activation

5-years Continuous Dynamic Monitoring

Histograms of maximum daily accelerations (Jun 2007- May 2010)



Lateral vibrations



Vertical vibrations

Santo Tirso footbridge
Excessive vertical vibrations

Steel arch, 60m chord, 6 m rise

Length= 84 m; Width: 5 m

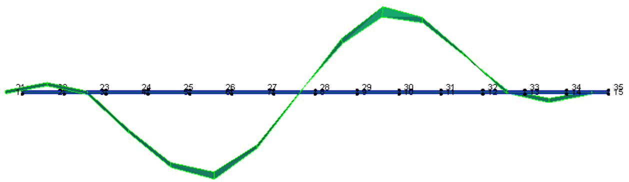
Deck: 0.15 m thick light weight concrete slab supported by steel girders

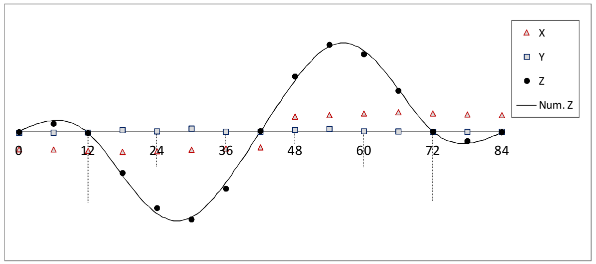
Designer: SOPSEC, Portugal

Experimental characterisation of the dynamic behaviour

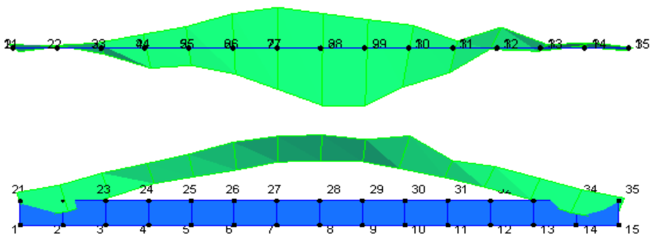
Natural frequency and mode configuration

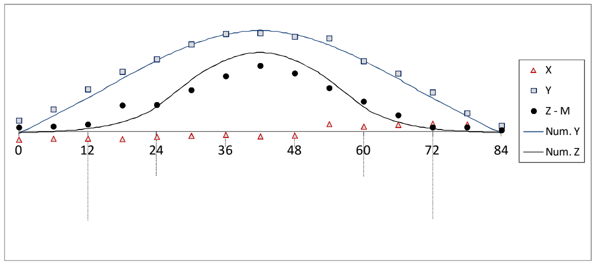
F_1=1.64 Hz; ξ_1=1,34% (calculated: **1.50** Hz)



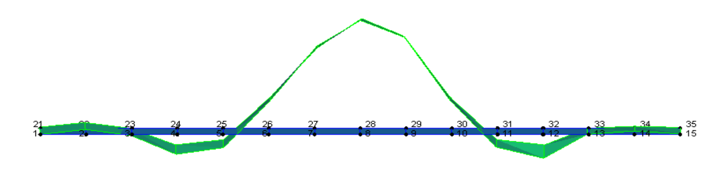


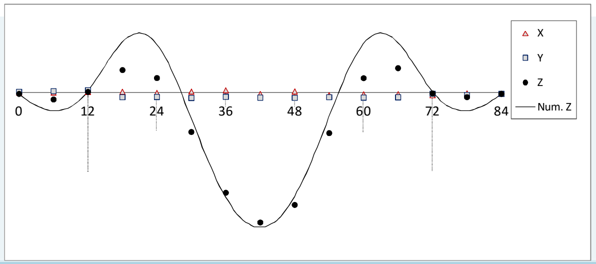
F_2=2.03 Hz; ξ_2=0,93% (calculated: **2.45** Hz)





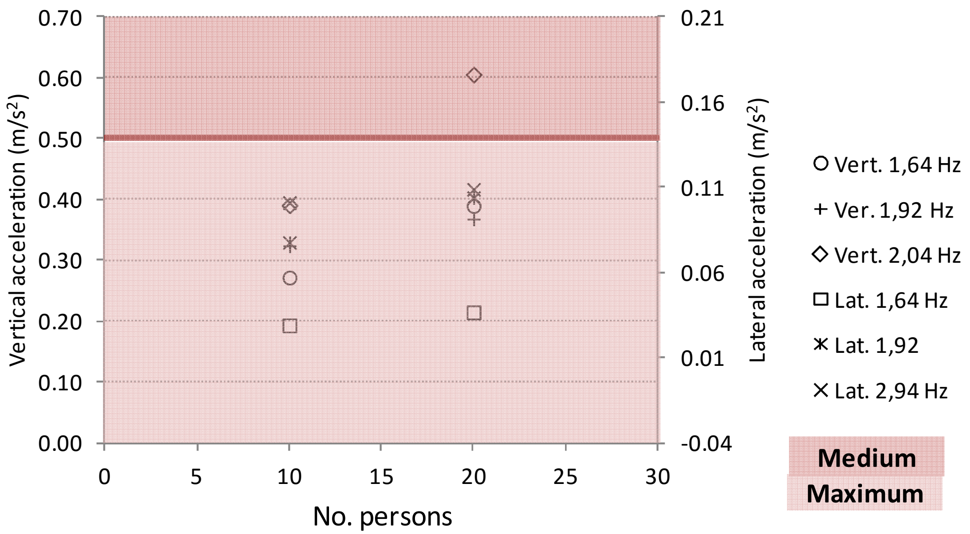
F_3=2.71 Hz; ξ_3=0,60% (calculated: **2.88** Hz)

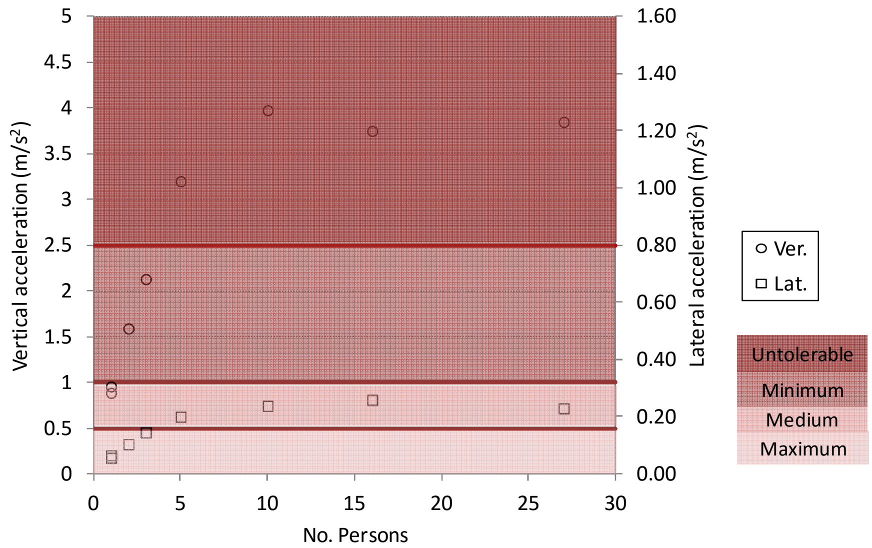




Experimental characterisation of the dynamic behaviour

Pedestrian tests





Crowd walking

(1/10th design number of pedestrians)

(estimated with 0.5P/m² : 1.5 m/s²)

Jogging

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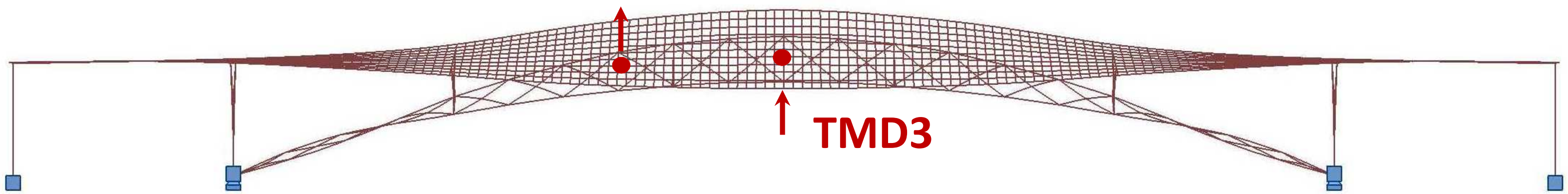
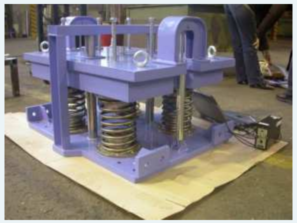
Vibration mitigation measures



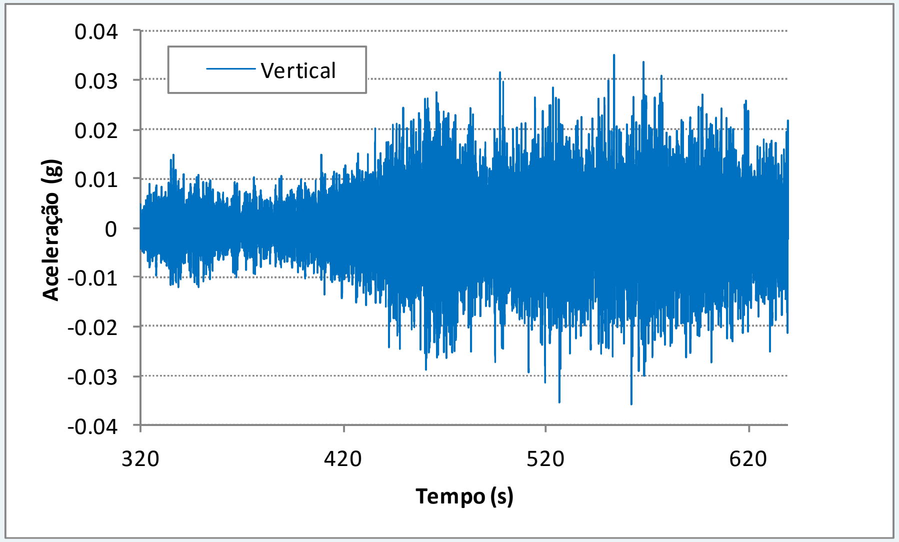
Mode/ TMD	Frequency (Hz)	Modal mass (kg)	Characteristics of TMDs				
			Freq. $_{TMD}$ (Hz)	Mass TMD (kg)	K_{TMD} (N/m)	C_{TMD} (Ns/m)	Rel. displ (mm)
1	1.59	81544	1.56	**1400 (1.7%)**	135050	2150	±100
3	2.65	40792	2.61	**700 (1.7%)**	187570	1790	±100

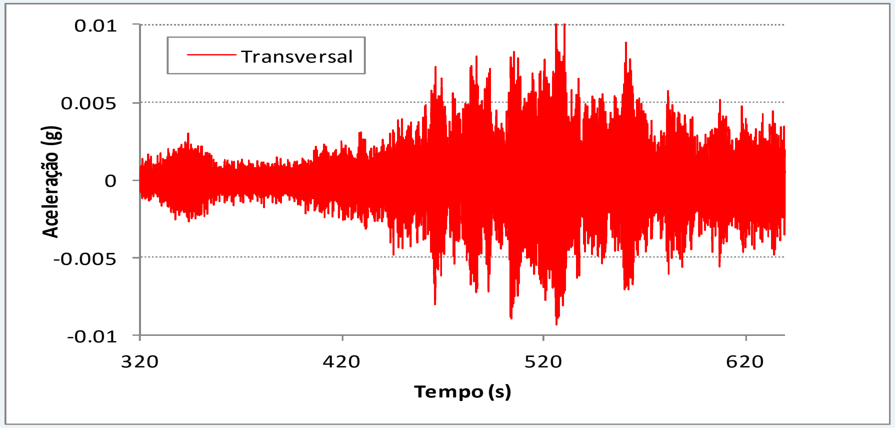


Verification of efficiency of installed TMDs

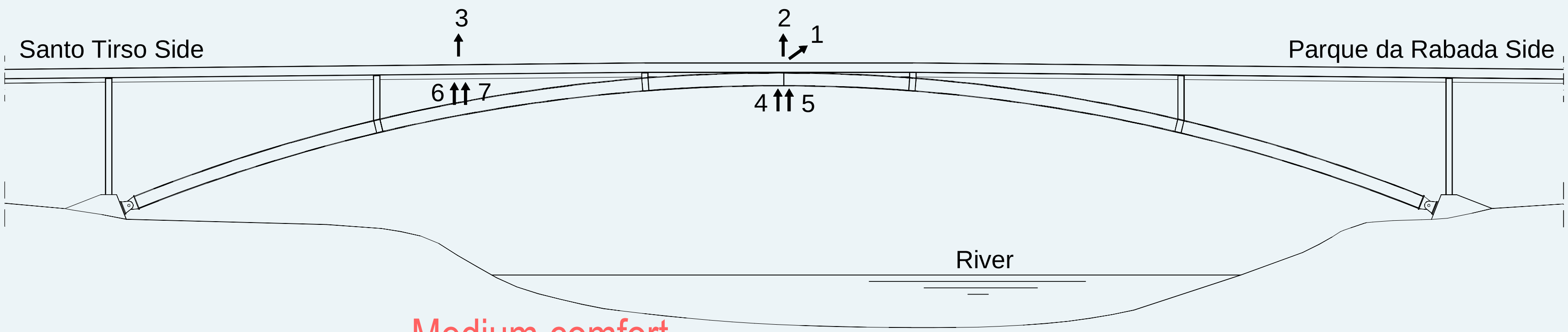
Innauguration

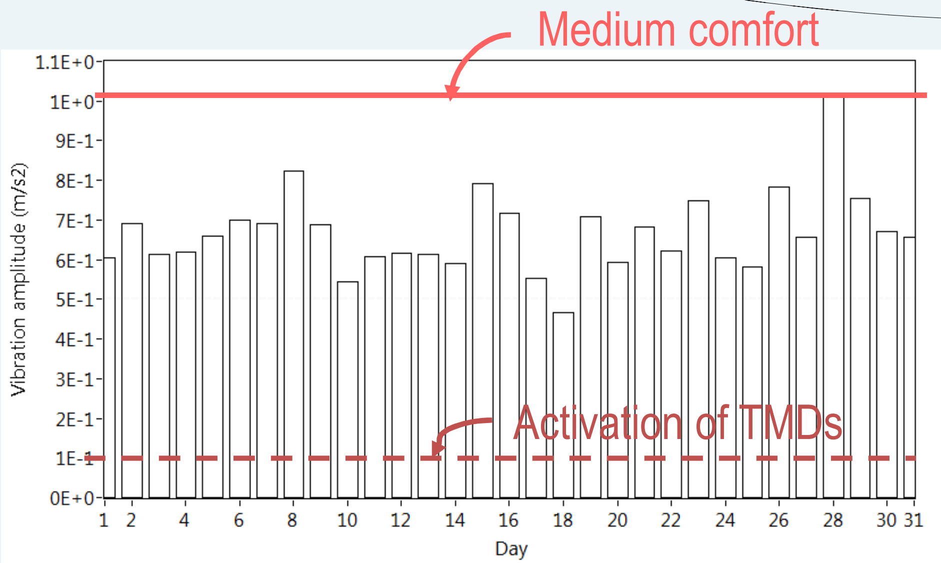
Maximum acceleration:
Vertical: 0.35 m/s²
Lateral: 0.1 m/²
Maximum comfort



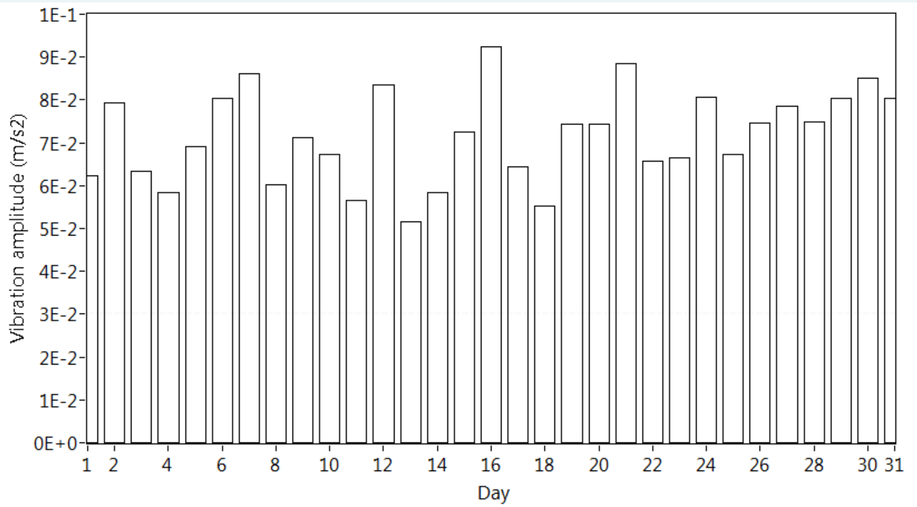


Continuous Dynamic Monitoring





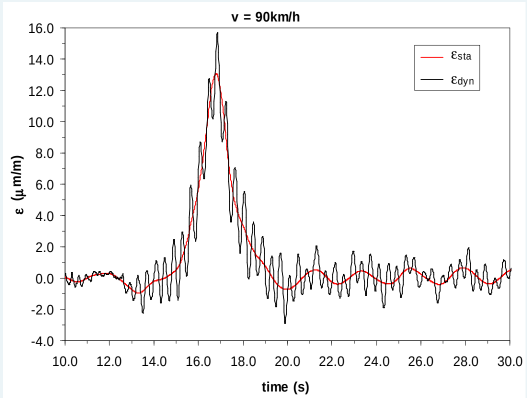
Maximum vertical daily acceleration

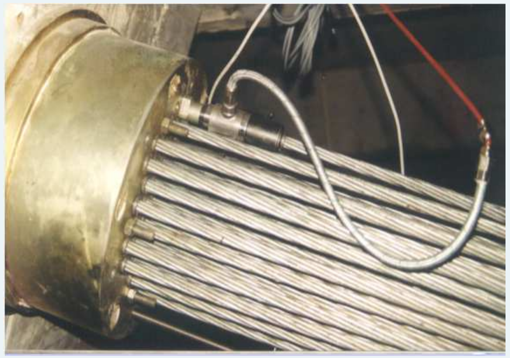


Maximum transversal daily acceleration

Temporary Monitoring Traffic induced vibrations in Roadway Bridges

- Salgueiro Maia cable-stayed bridge
- Dynamic effects due to heavy traffic



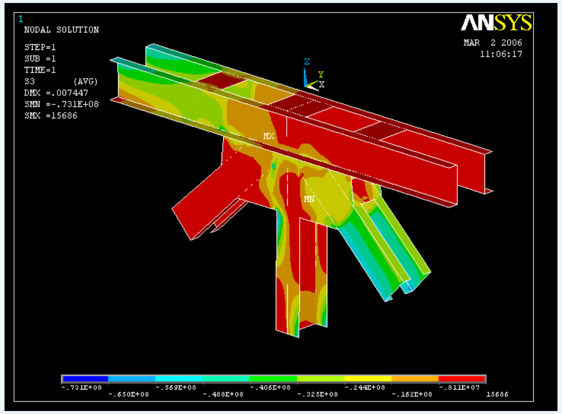


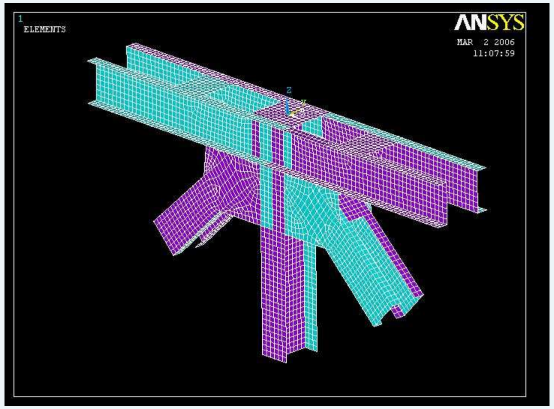
Load cells in stay cables

Embeded strain gages

Monitoring Traffic induced vibrations in Railway Bridges and Fatigue assessment

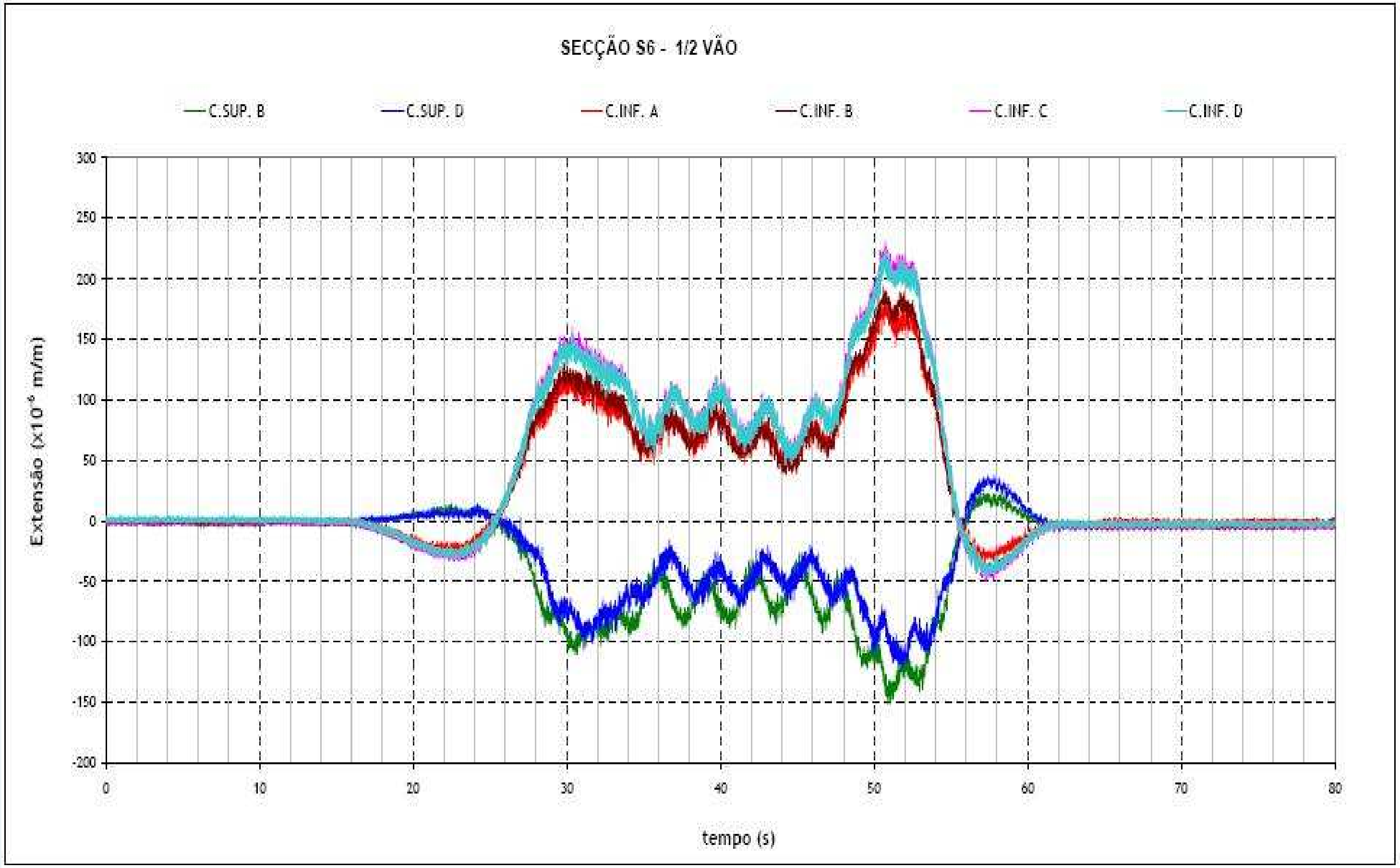
- **Dynamic effects and fatigue assessment if Trezói Bridge**

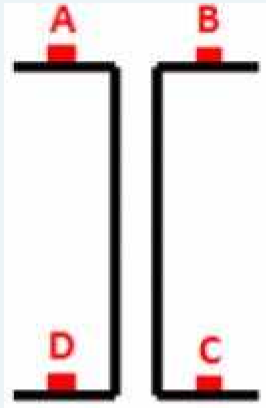




Monitoring Traffic induced vibrations in Railway Bridges and Fatigue assessment

Strain measurements under traffic loads

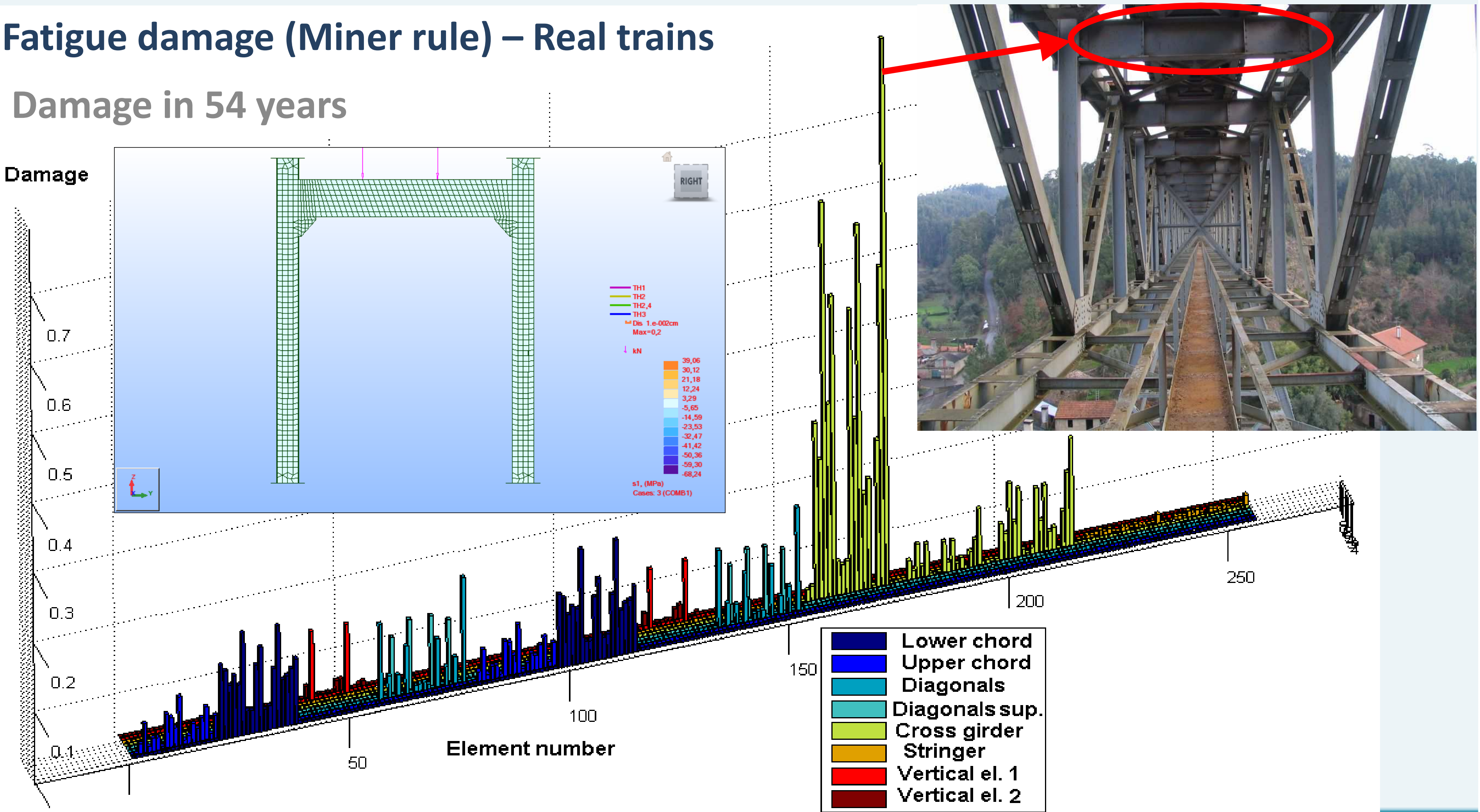




Monitoring Traffic induced vibrations in Railway Bridges and Fatigue assessment

Fatigue damage (Miner rule) – Real trains

Damage in 54 years



Continuous Dynamic Monitoring for Damage Detection

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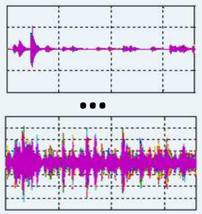
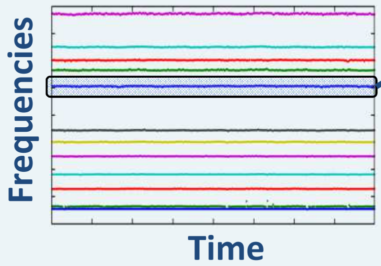
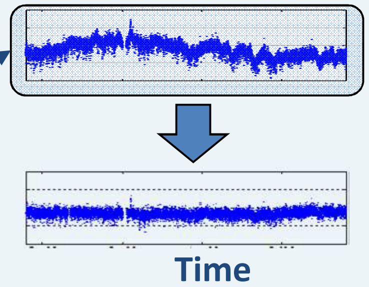
Vibration based Structural Health Monitoring Processing Strategy



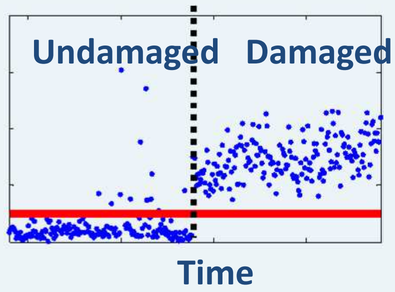
Continuous acquisition of acceleration time series



Automatic identification of modal parameters



Extraction of environmental and operational effects (temperature, traffic, …)



Calculation of an index able to flag relevant frequency shifts

(Damage Detection)

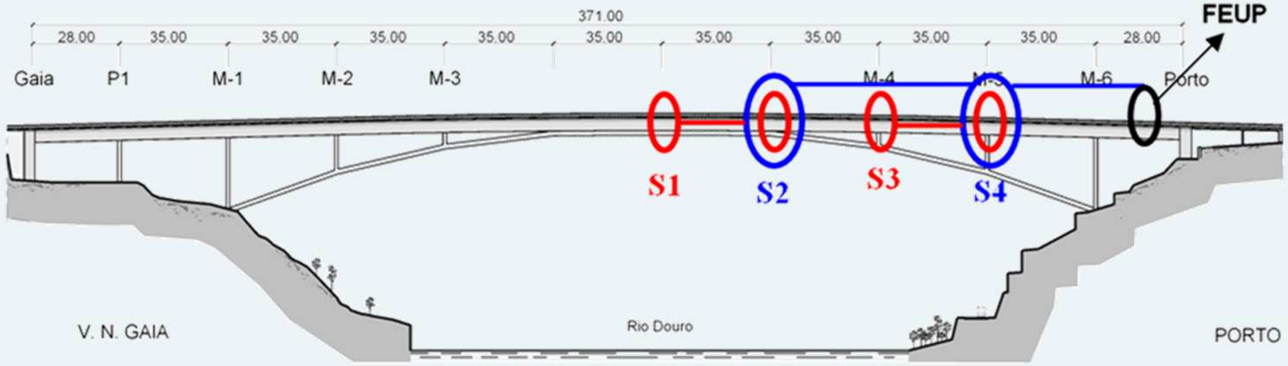
DYNAMO software for Dynamic Monitoring

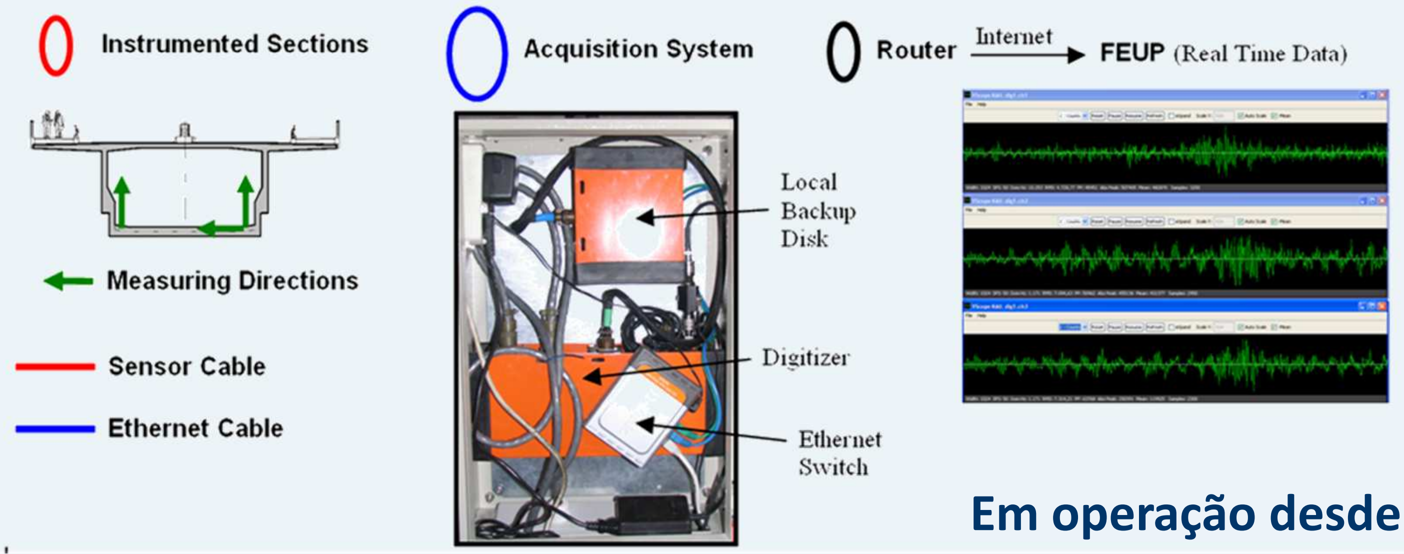
Automated
FDD
SSI-COV
p-LSCF

Regression Models
PCA

Control charts

Dynamic Monitoring System

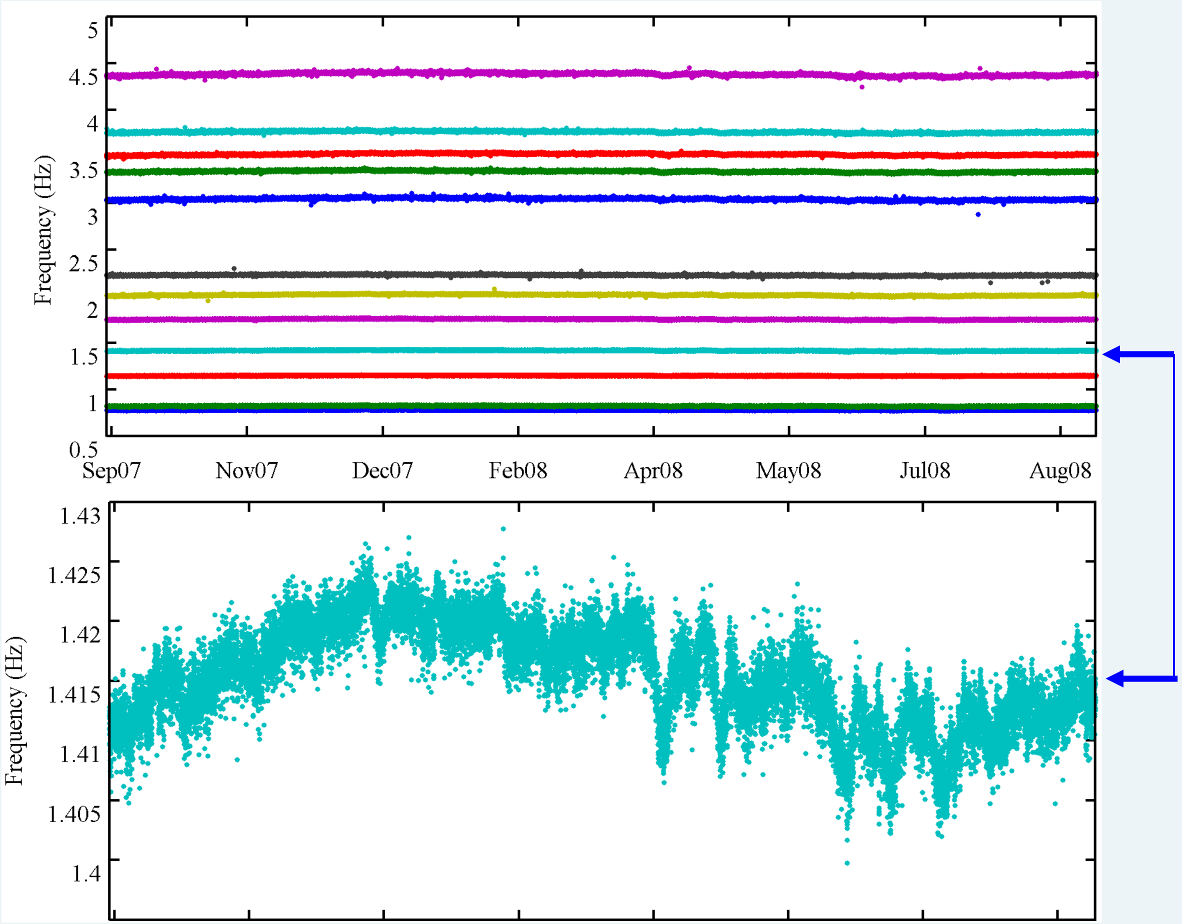




Em operação desde Setembro 2007

Results from one year of Continuous Monitoring

Variation of the first 12 natural frequencies (p-LSCF)

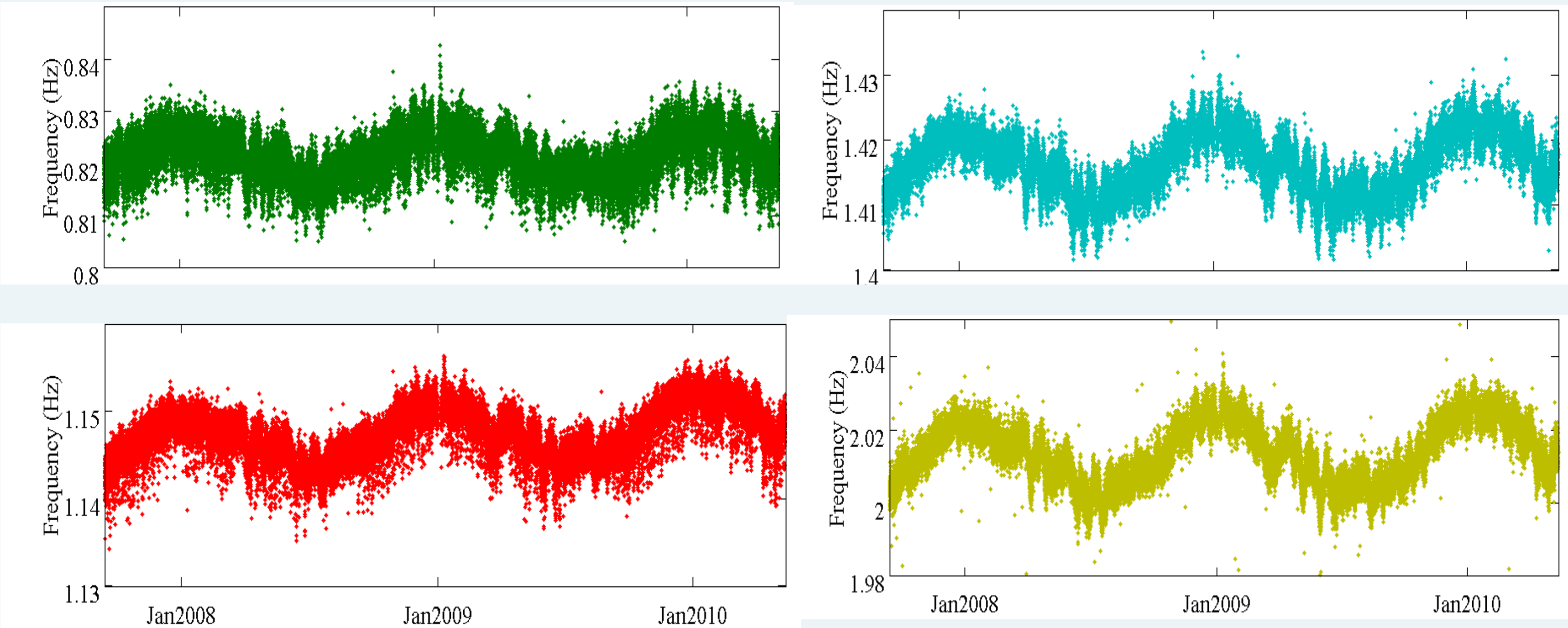


Identification success rates (17 325 setups)

Mode	Success rate (%)
1	99.99
2	99.99
3	100
4	100
5	99.94
6	99.33
7	99.87
8	100
9	99.90
10	99.04
11	99.67
12	100

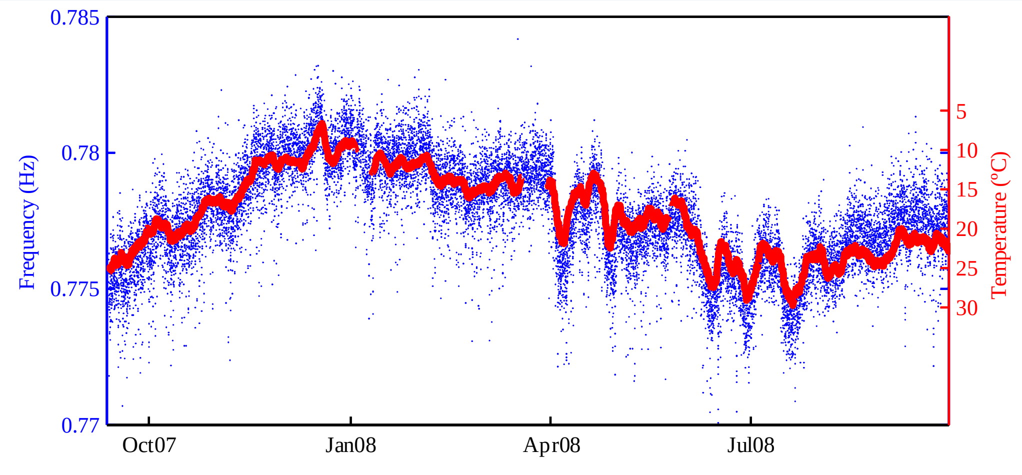
Results from 3 years of Continuous Monitoring

Variation of the 4 first natural frequencies along 3 years



Removal of Environmental and Operational Effects

Selection of variables with influence on the natural frequencies

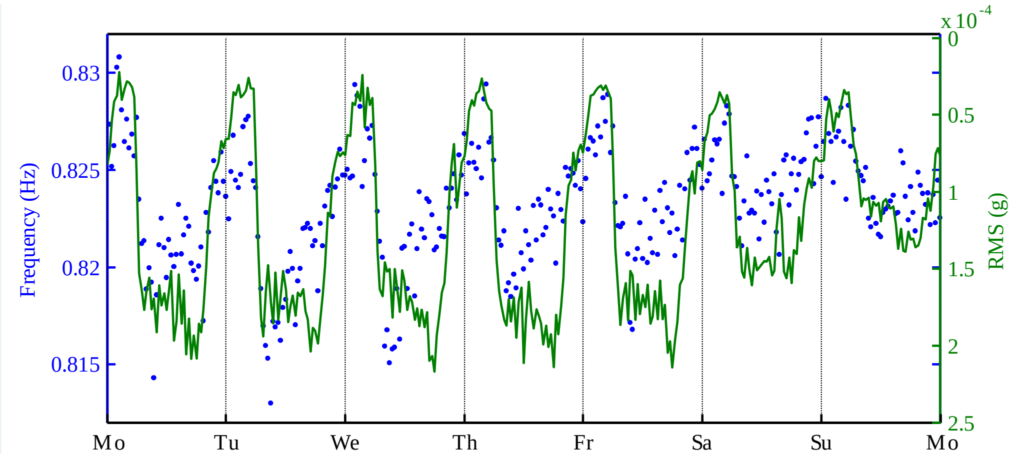


First natural frequency

vs

Temperature at the top of section T3

Two selected temperatures (top and bottom deck zones)



Second natural frequency

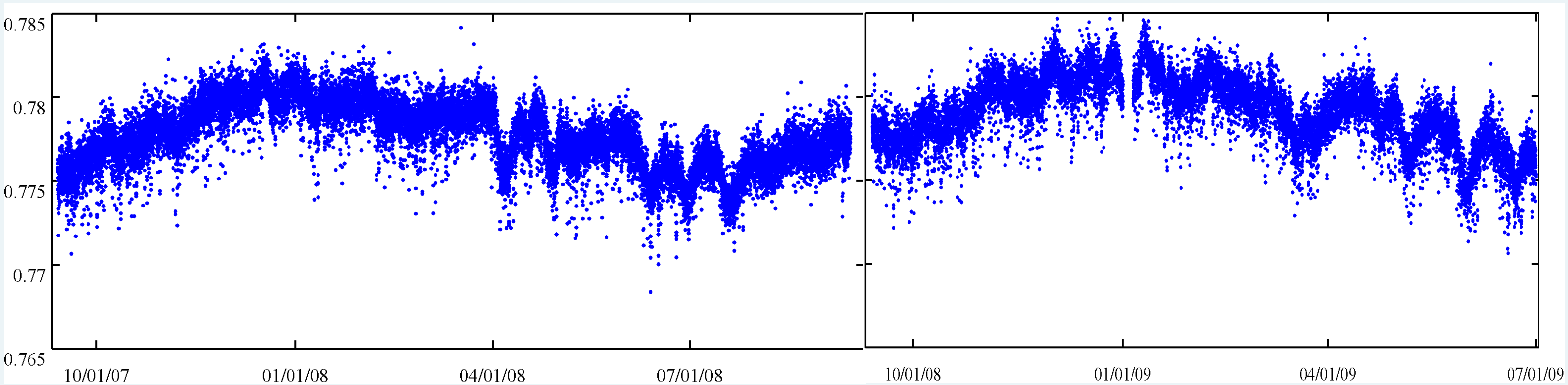
vs

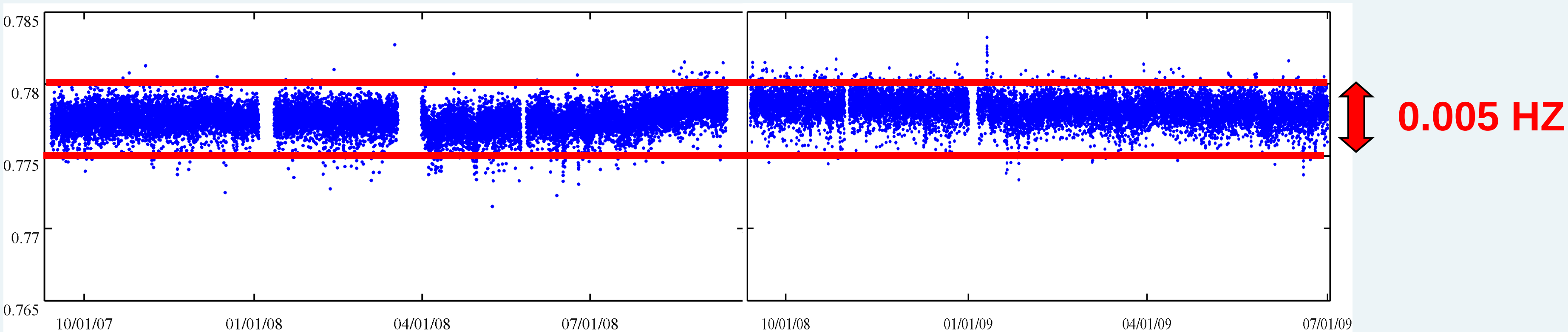
RMS of vertical accelerations at S3

Two RMS selected (vertical and lateral)

Removal of Environmental and Operational Effects

Multiple regression model

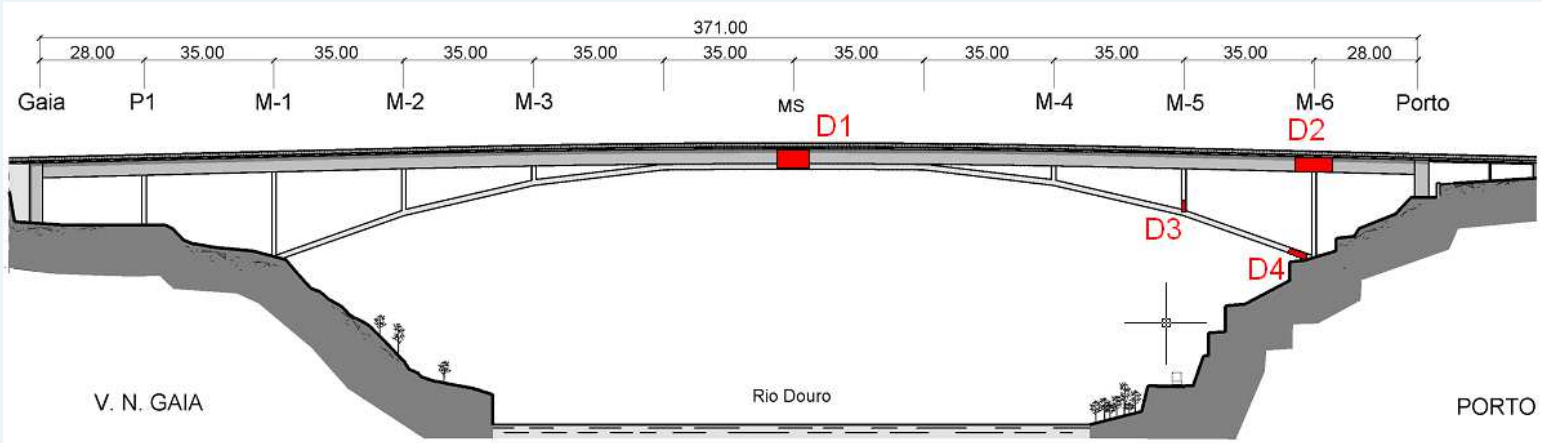




Detection of damage associated to very small frequency variations

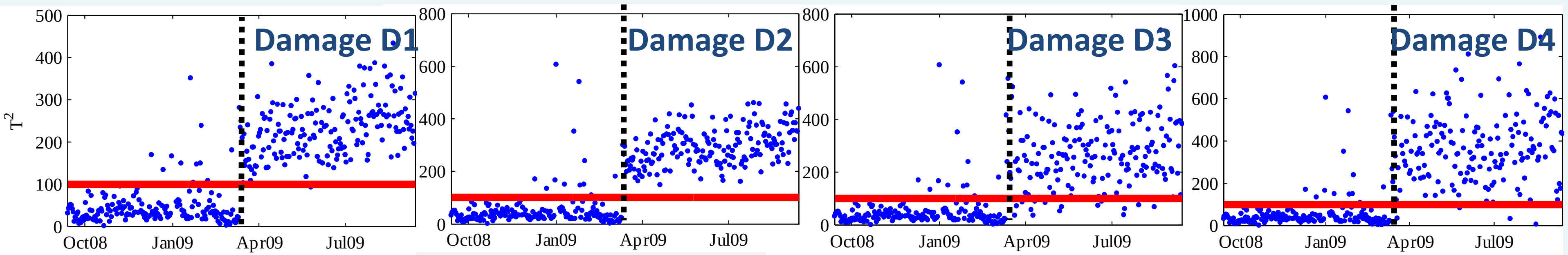
Dynamic Monitoring for Damage Detection

Numerical simulation of 4 damage scenarios

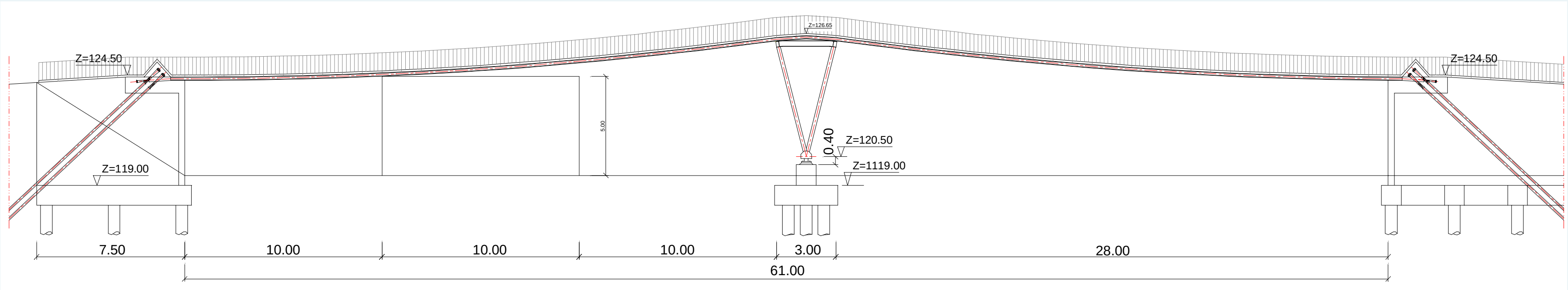


Variations of 10 % in vertical bending inertia of small segments (3 to 10 meters)

Relative variations of natural frequencies of about 0.2%

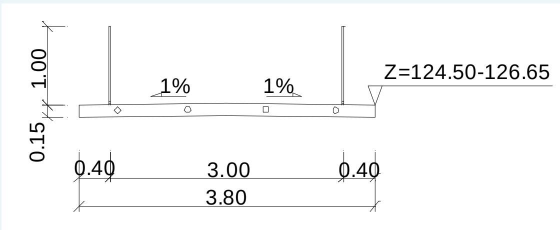


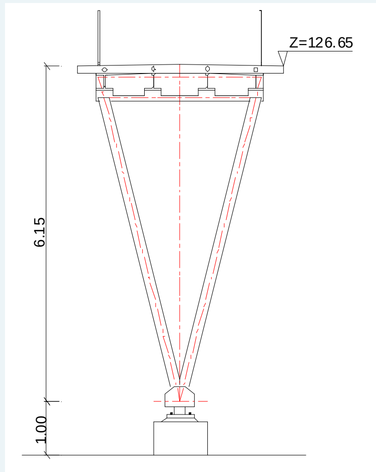
FEUP stress-ribbon footbridge
Vibration based SHM



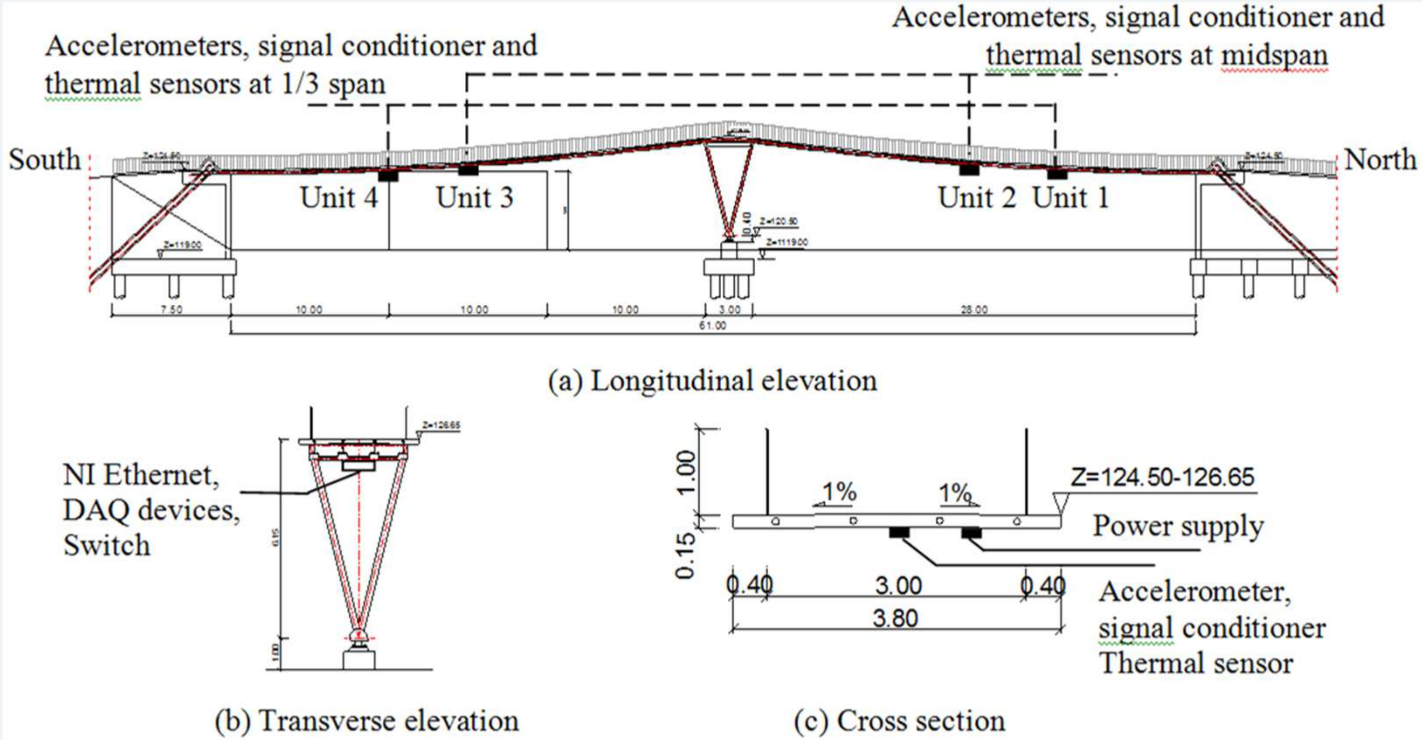
L_1=30m; L_2=28m

T_0=750kN x 4



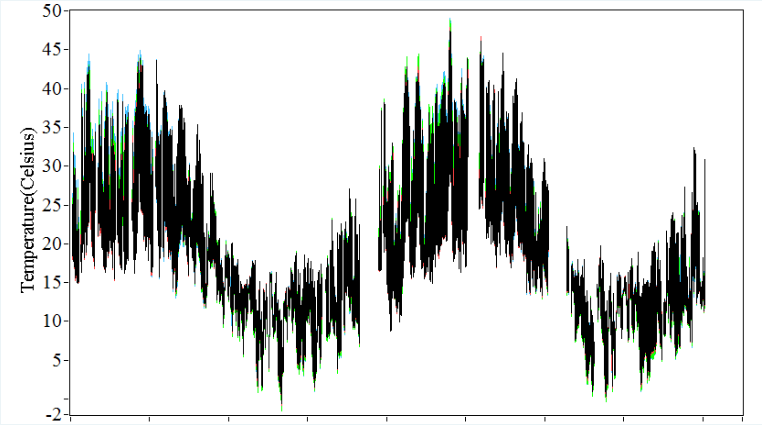


Continuous Dynamic Monitoring System implemented on FEUP Campus Footbridge

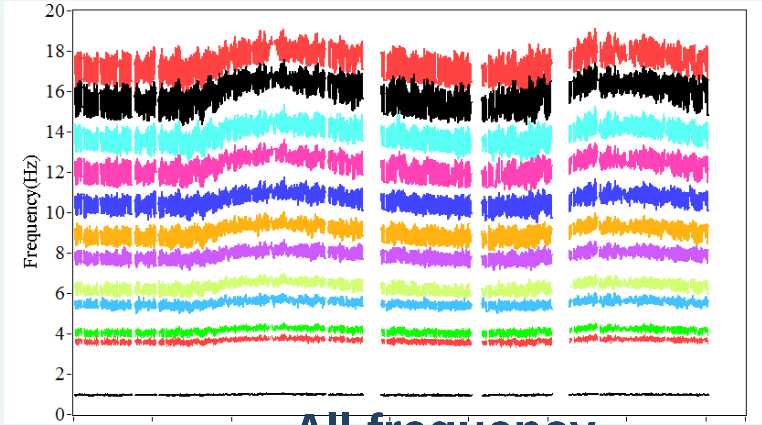


Elevations and cross section of the footbridge, with indication of the components of the installed continuous dynamic monitoring system

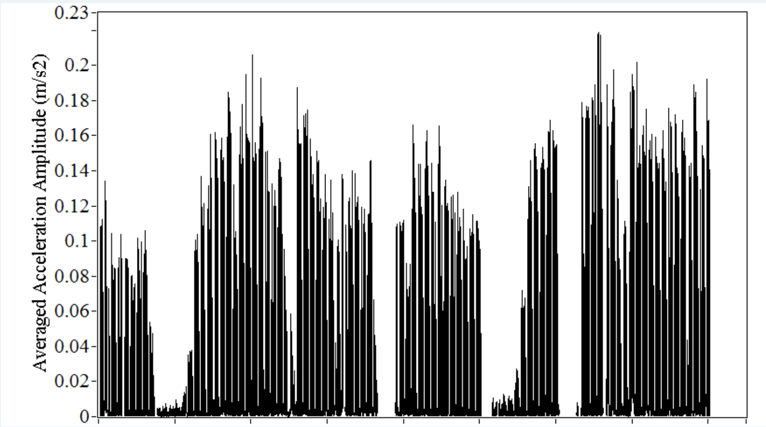
Monitoring results from 1st June 2009 to 31st March 2011



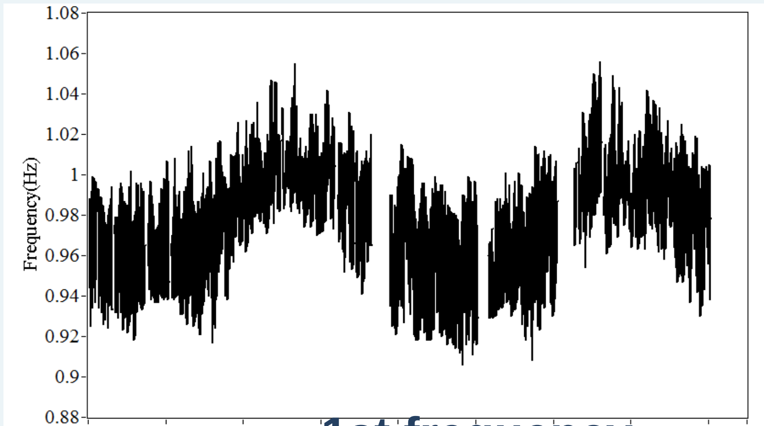
Temperature records in different positions



All frequency estimates



Averaged acceleration amplitude



1st frequency estimates

Monitoring results from 1st June 2009 to 31st March 2011

Variations of natural frequency estimates

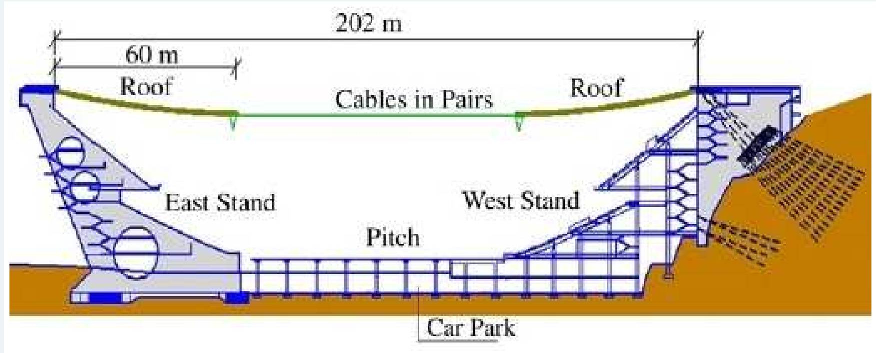
Mode order	Average frequency (Hz)	Interval (Hz)	Max. rel. difference (%)
1	0.981	0.906-1.056	15.3
5	3.671	3.337-4.007	18.3
6	4.171	3.745-4.563	19.6
7	5.508	4.987-6.046	19.2
8	6.379	5.766-7.021	19.7
9	7.909	7.114-8.693	20.0
10	9.096	8.124-10.030	20.9
11	10.623	9.487-11.758	21.4
12	12.348	11.031-13.624	21.0
13	13.919	12.480-15.382	20.8
14	16.004	14.330-17.597	20.4
15	17.492	15.714-19.158	19.7

Continuous Dynamic Monitoring for characterization of the aerodynamic behaviour

- **Braga Stadium suspension roof (EURO'2004)**

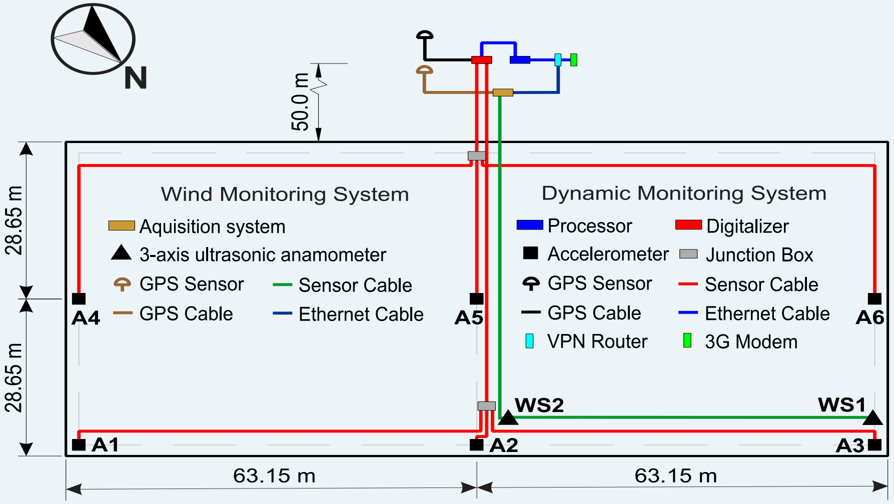
Top view of the stadium

Lateral view from west side

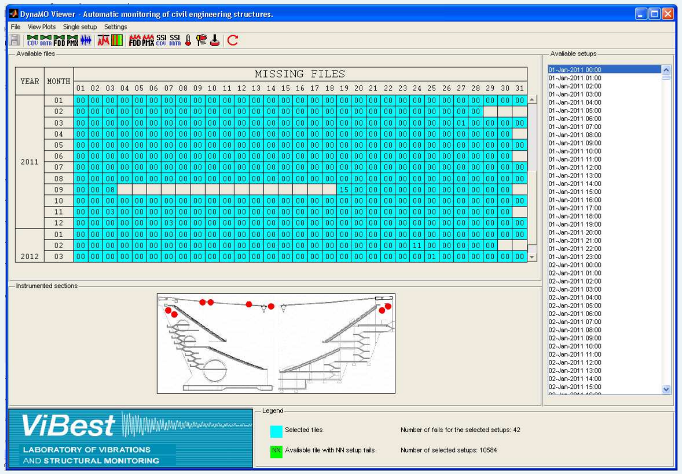


Cross section

Continuous wind and dynamic monitoring systems



- 6 force balance accelerometers
- 2 sonic anemometers
- 8 temperature sensors
- Continuous sampling at 20 Hz/ 10Hz
- Records with 30 minutes duration
- Data transfer to a server at FEUP

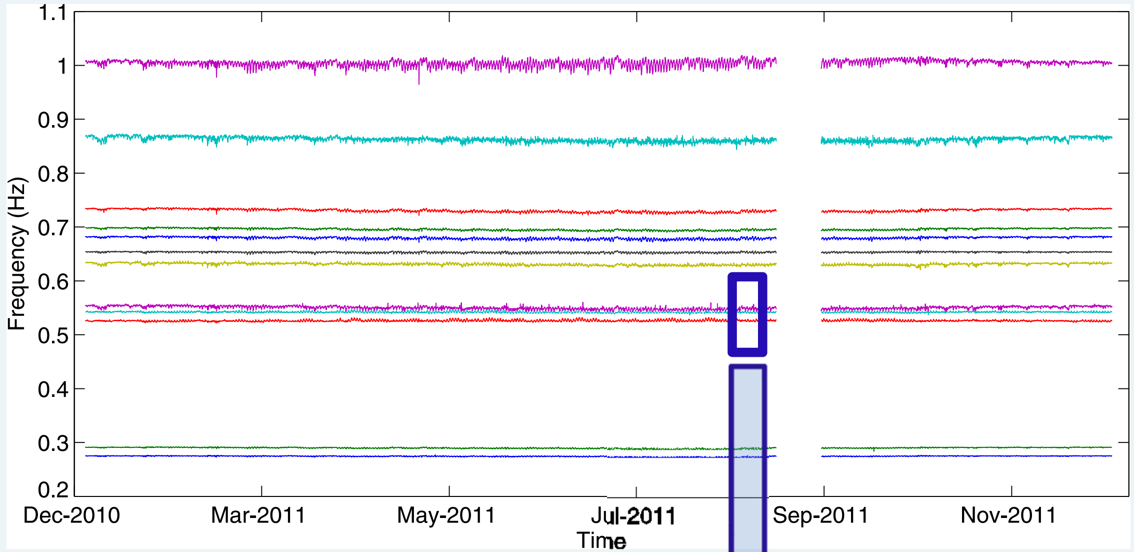


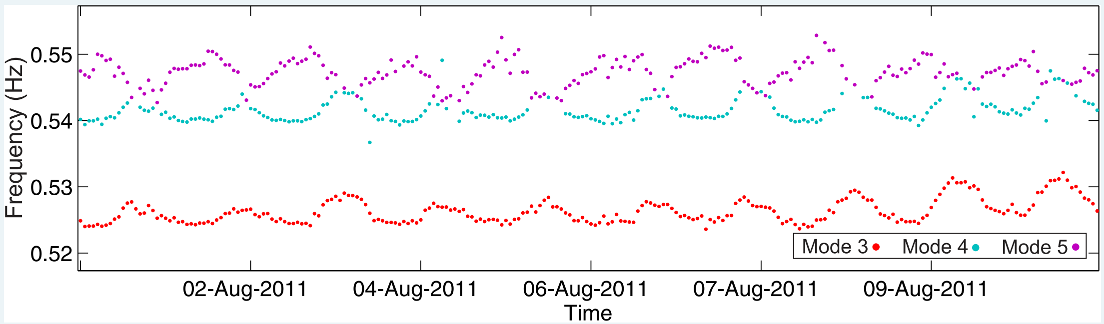
Active since March 2009

Estimates of modal parameters

- One-year variation of identified natural frequencies (p-LSCF)

One-year monitoring
(from 01/01 to 31/12/2011)

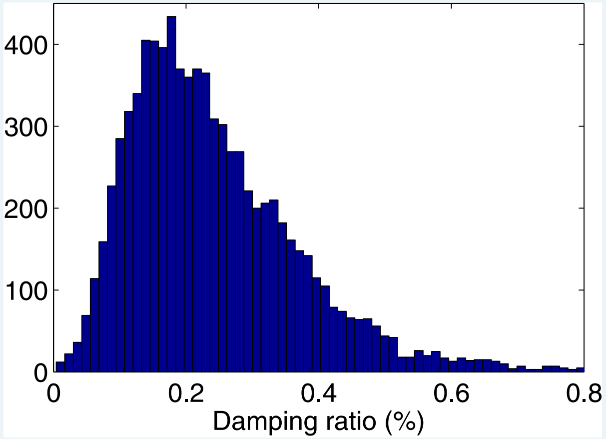




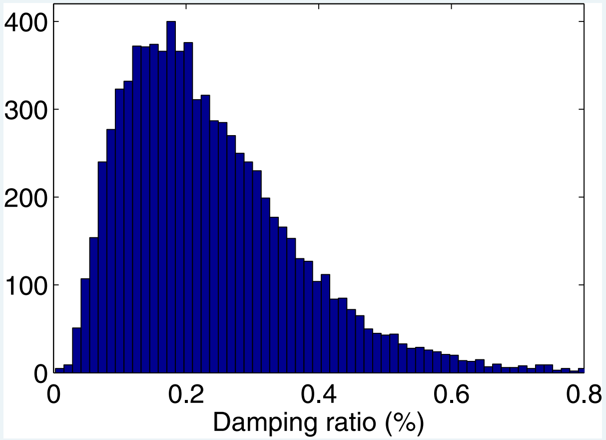
Ten days monitoring of modes
3, 4 and 5
(1 to 10/08/2011)

Estimates of modal parameters

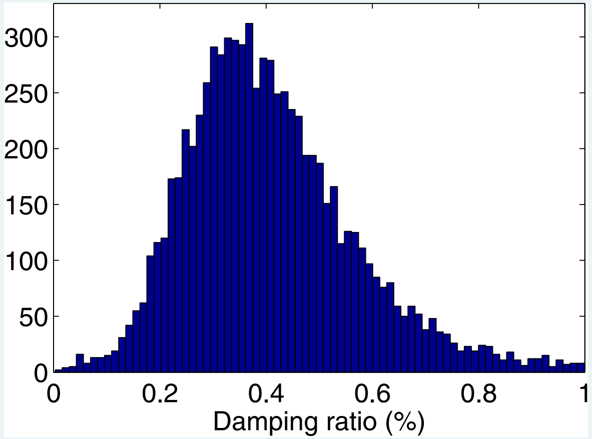
- **Dispersion of the Identified damping Ratios (pLSCF)**



Mode 1



Mode 2

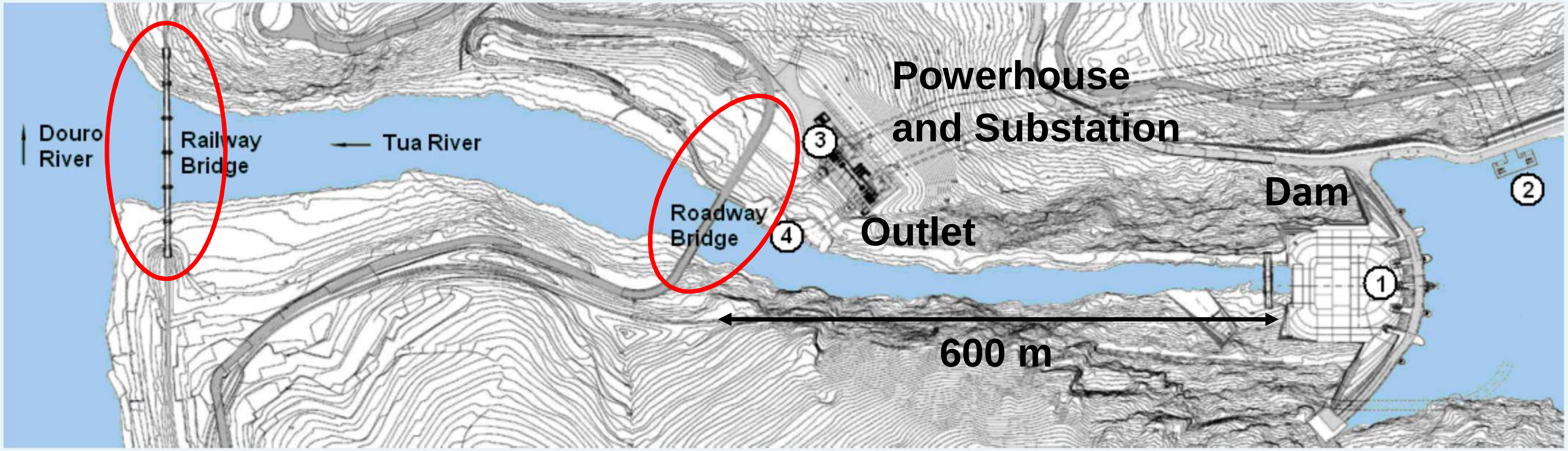


Mode 5

Dynamic monitoring of two bridges in a dam construction site

Filipe Magalhães; Álvaro Cunha
(www.fe.up.pt/vibest)

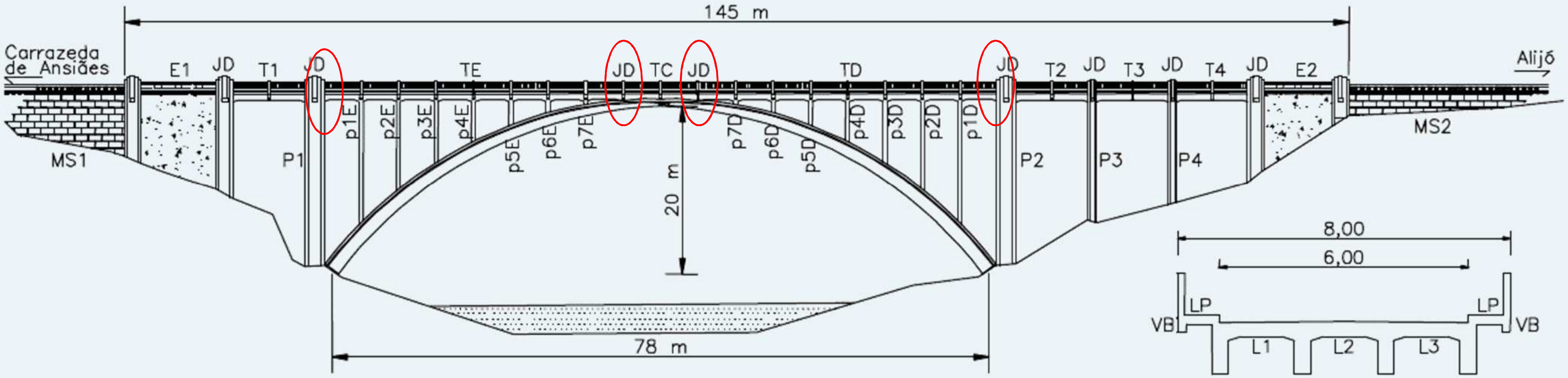
Dam Construction Site



Relevant construction activities:

- rock blasting
- heavy trucks crossing the roadway bridge
- deepening of the river bed
- Retrofit of the railway bridge foundations

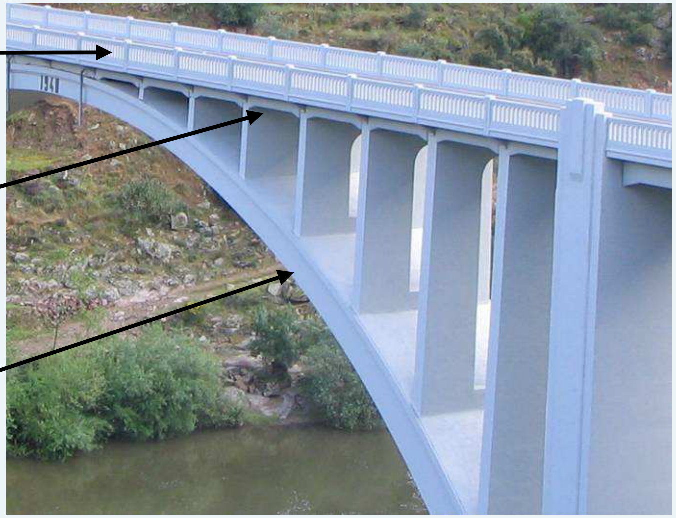
Roadway Bridge



Concrete handrails

Reinforced concrete beams stiffened with steel plates

Plain concrete arch



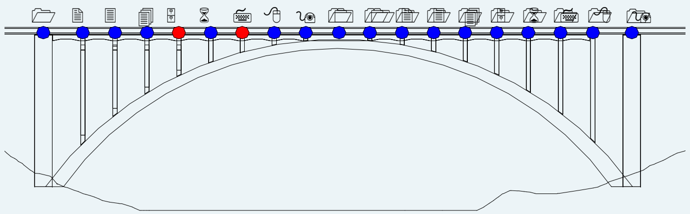
Built in 1940

Rehabilitated in 2007

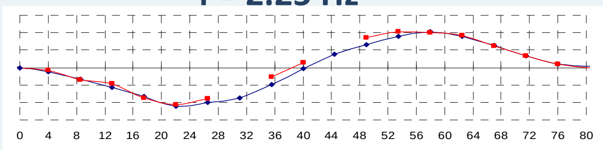
- stiffing of the deck
- replacement of the handrails
- replacement of the supports and dilation joints
- surface repair and painting

Roadway Bridge - Ambient Vibration Test

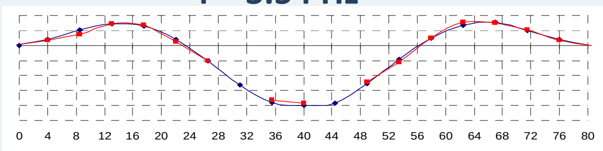
Vertical Bending



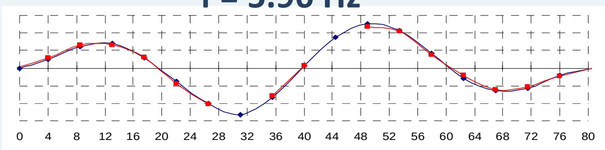
f = 2.25 Hz



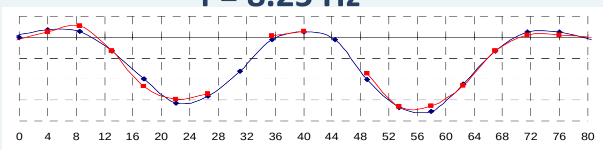
f = 3.54 Hz



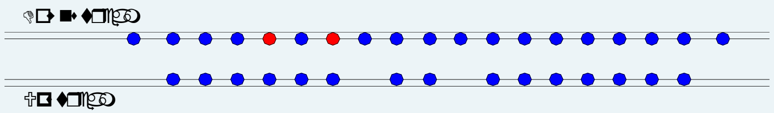
f = 5.96 Hz



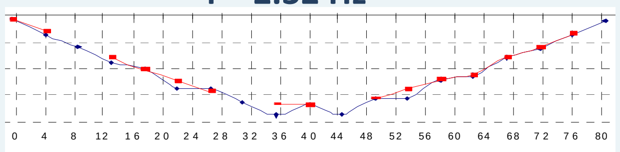
f = 8.25 Hz



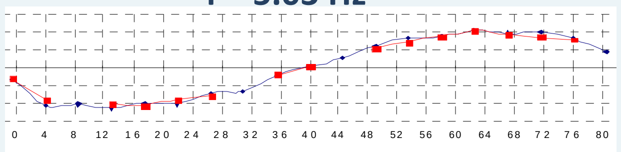
Lateral Bending



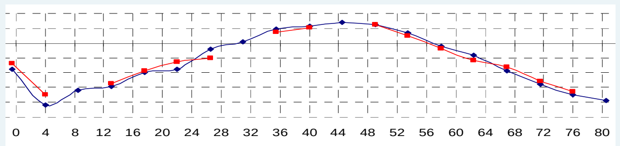
f = 2.32 Hz



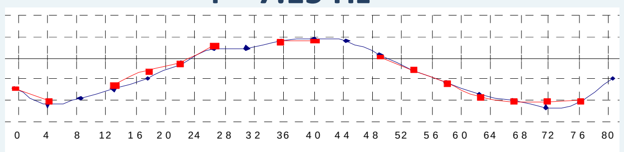
f = 5.03 Hz



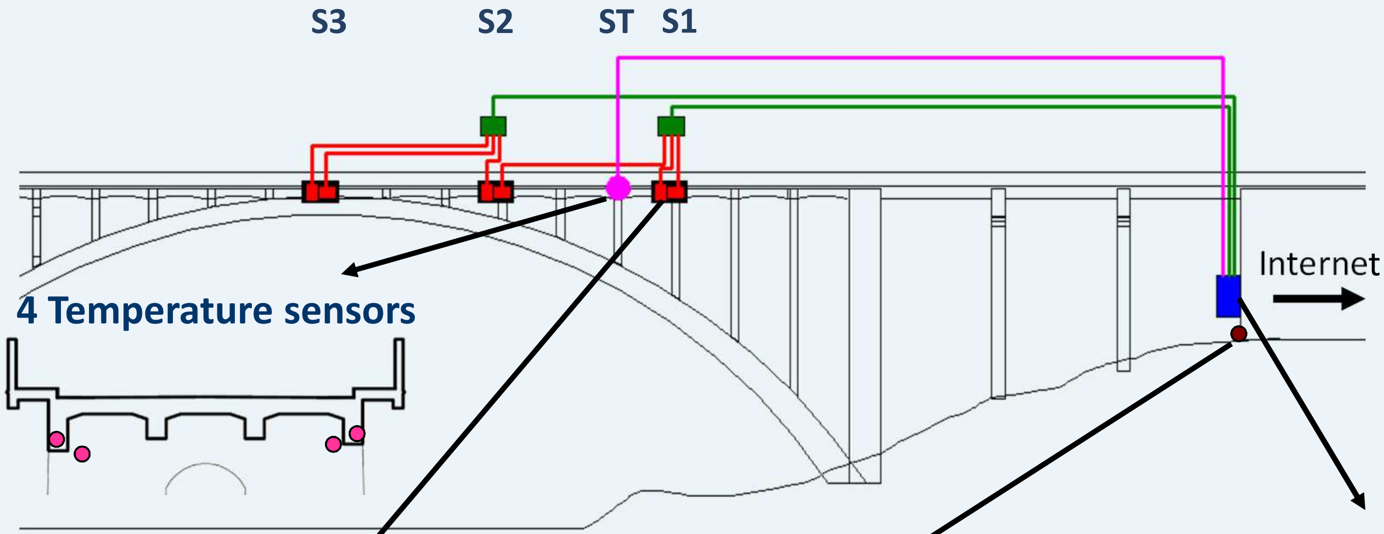
f = 6.40 Hz



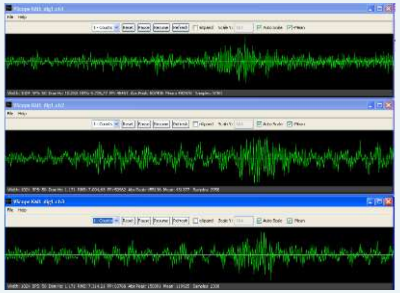
f = 7.15 Hz



Roadway Bridge - Monitoring System



ViBest (Real Time Data)



6 force balance accelerometers

2 tri-axial Geophones

24 bit digitizer

Field processor

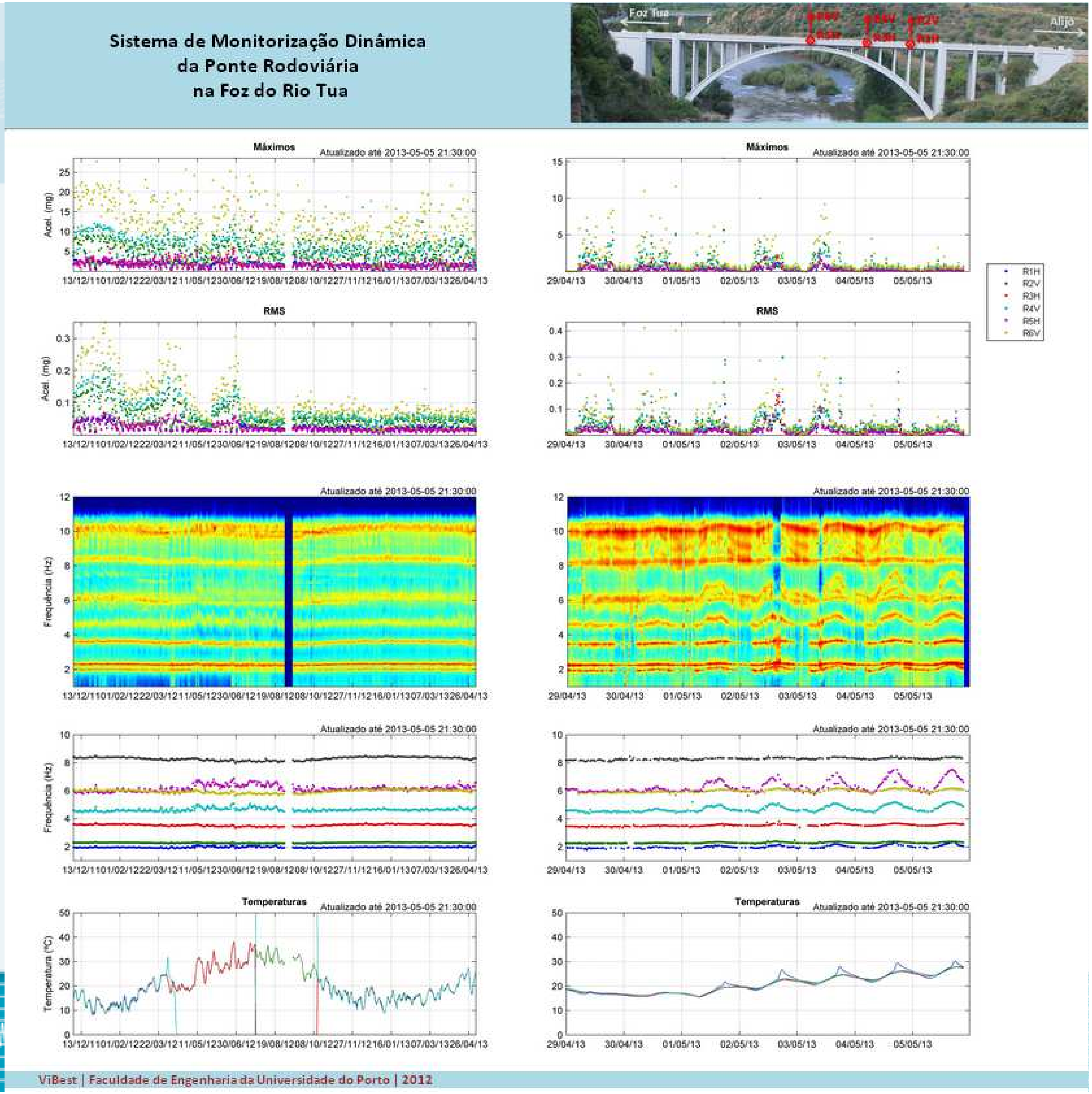
Blast monitoring system

In continuous operation since December 2011

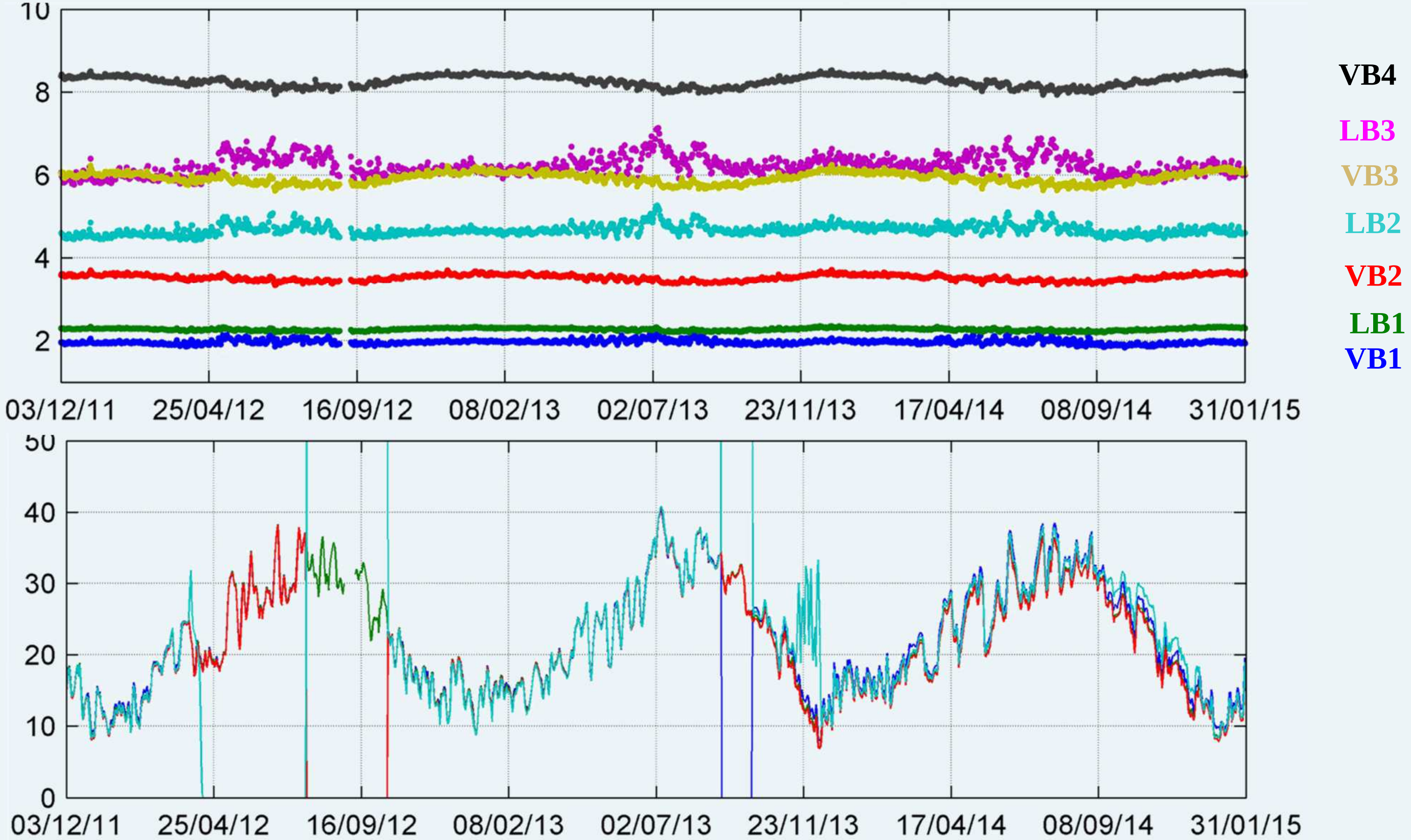
Monitoring Software

DynaMo Web page

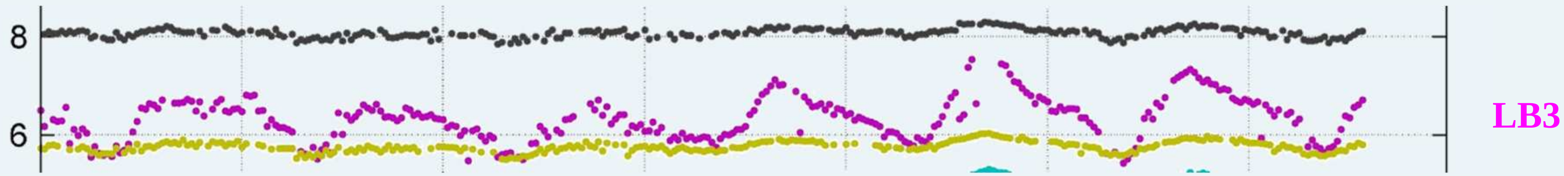
Updated every 30 minutes



Results Roadway Bridge (3 years)



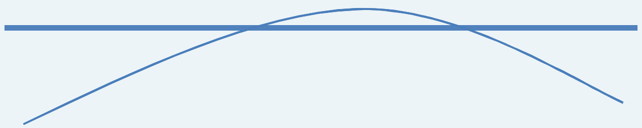
Roadway Bridge - Temperature effects



Lower temperatures

The support of the deck in the main piers allows free relative lateral displacements

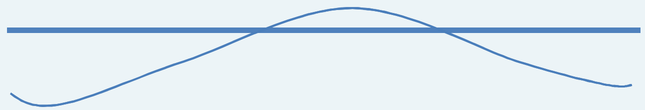
Mode shape in plan view



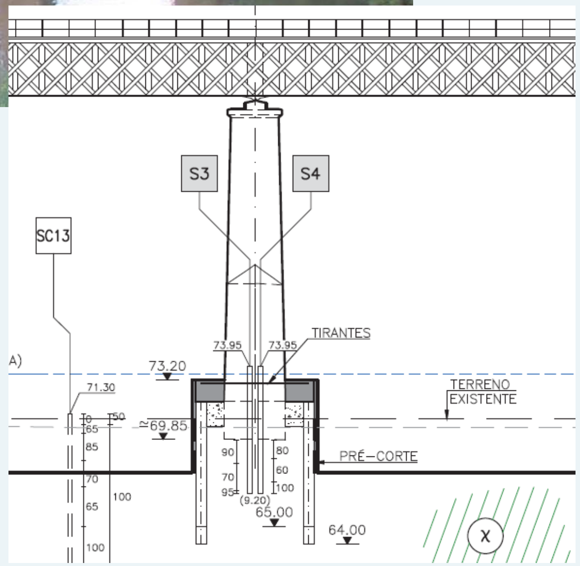
Higher temperatures

The expansion of the deck leads to a contact between deck and main piers that constrains relative lateral displacements

Mode shape in plan view



Railway Bridge



Built in 1882

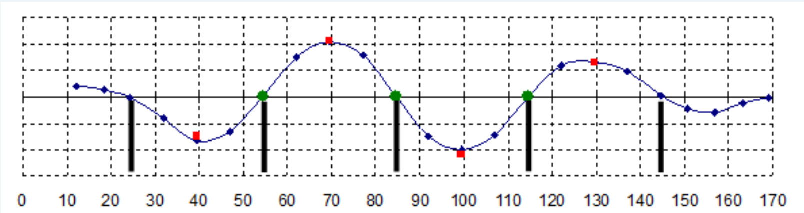
Steel riveted truss deck with a height of 3 meters and a total length of 169 meters

Deepening of the river bed of about 3m

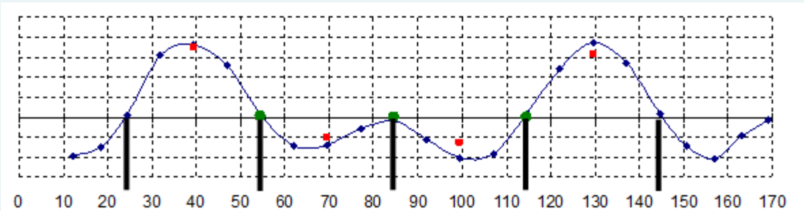
Railway Bridge - Ambient Vibration Test

Vertical Bending

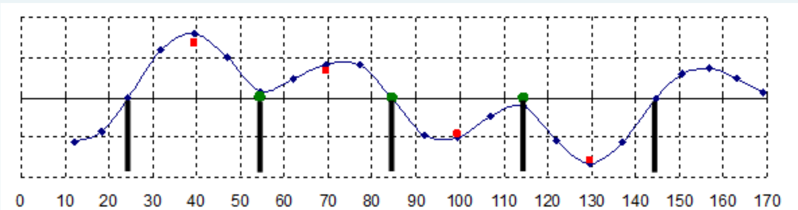
f = 6.42 Hz



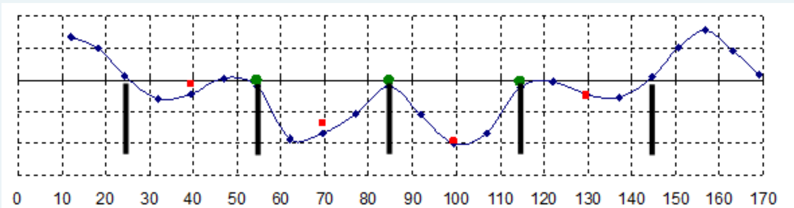
f = 7.20 Hz



f = 8.06 Hz

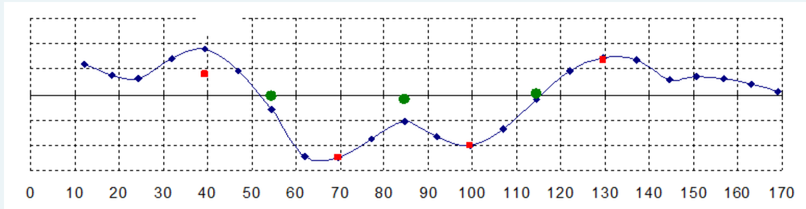


f = 9.38 Hz

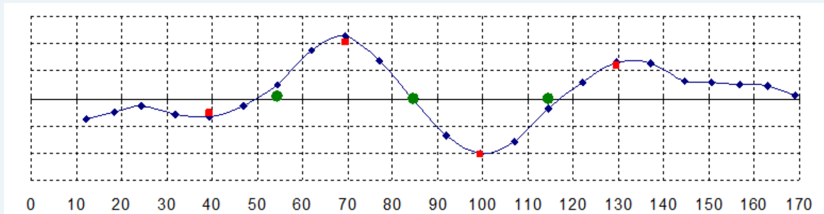


Lateral Bending

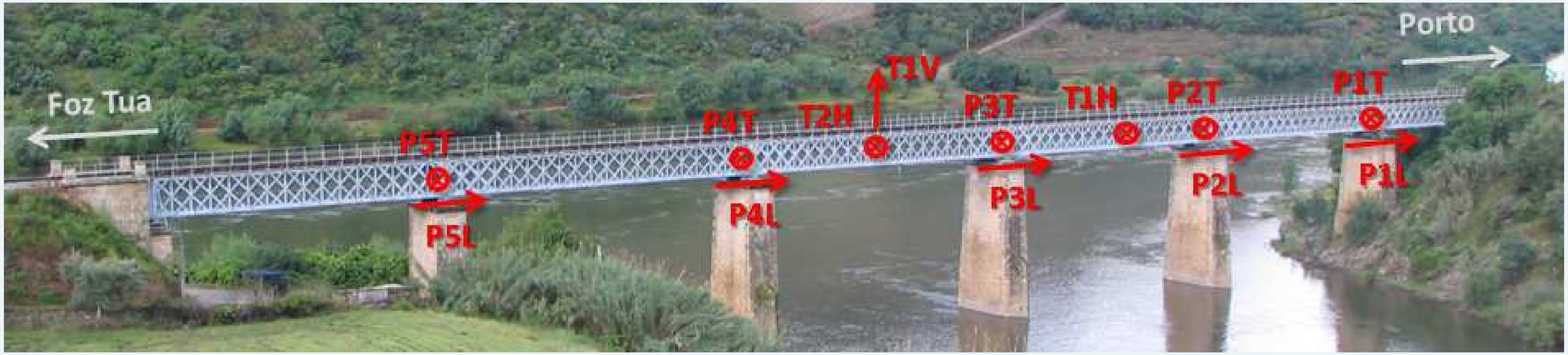
f = 4.10 Hz



f = 4.30 Hz



Railway Bridge - Monitoring System



13 force balance accelerometers

2 24-bit digitizers

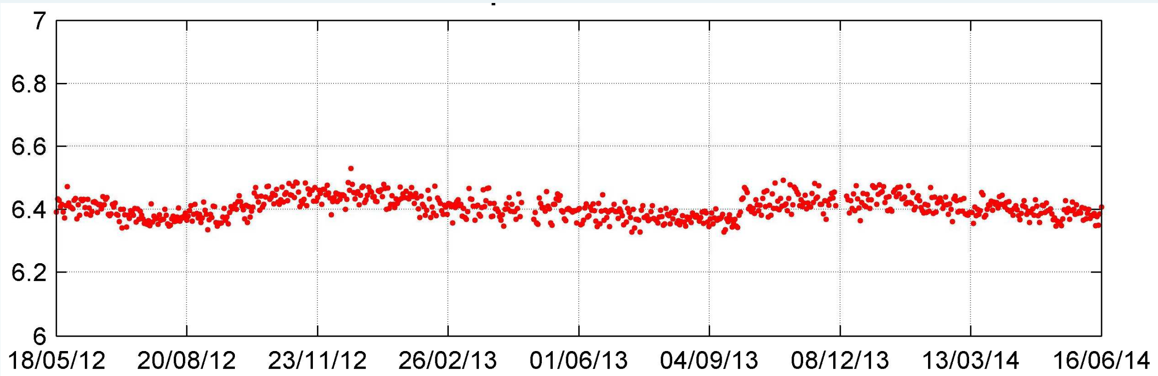
4 temperature sensors

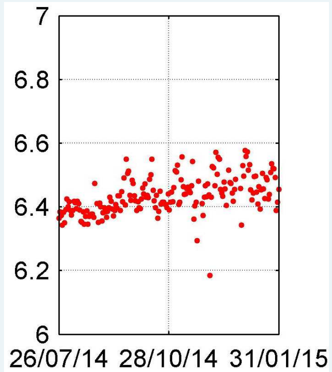
7 geophones

3 bi-axial clinometers

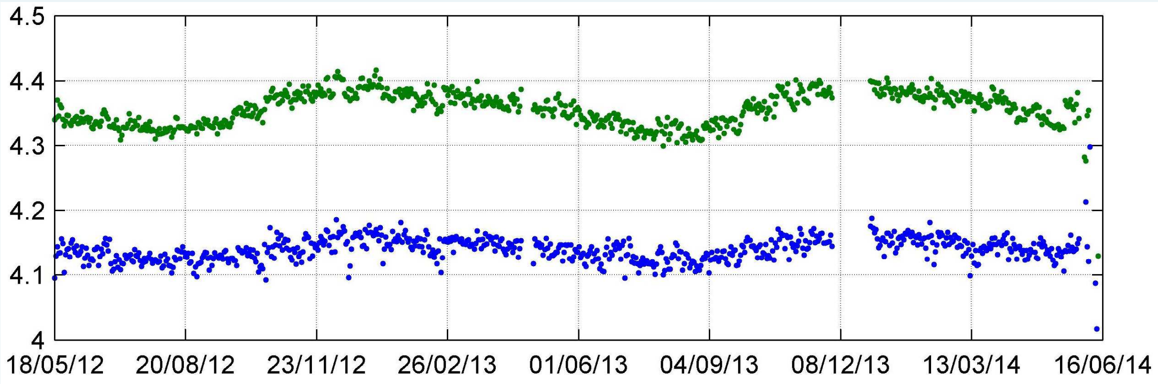
Results - Railway Bridge (2.5 years)

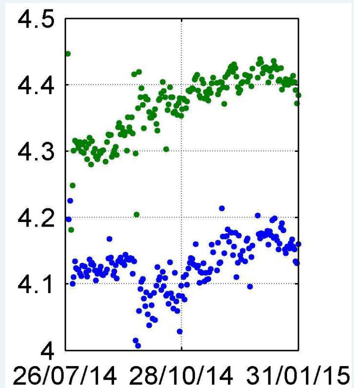
Bridge deck natural frequencies





Vertical

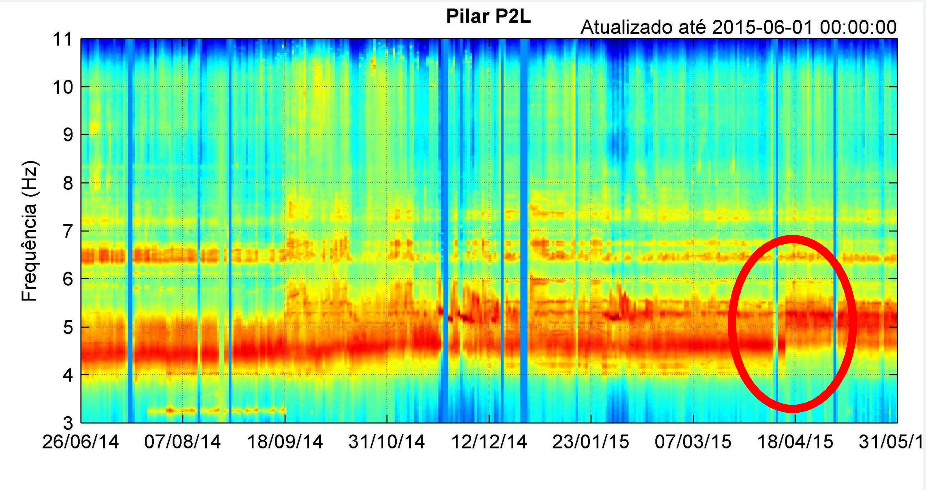




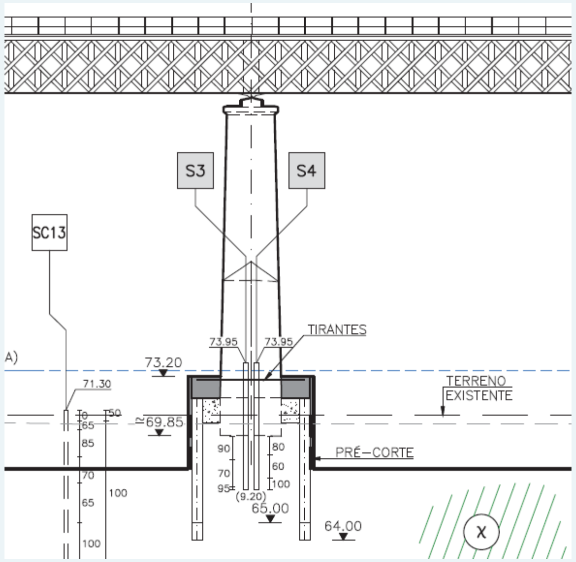
Lateral

Results - Railway Bridge

Piers natural frequencies

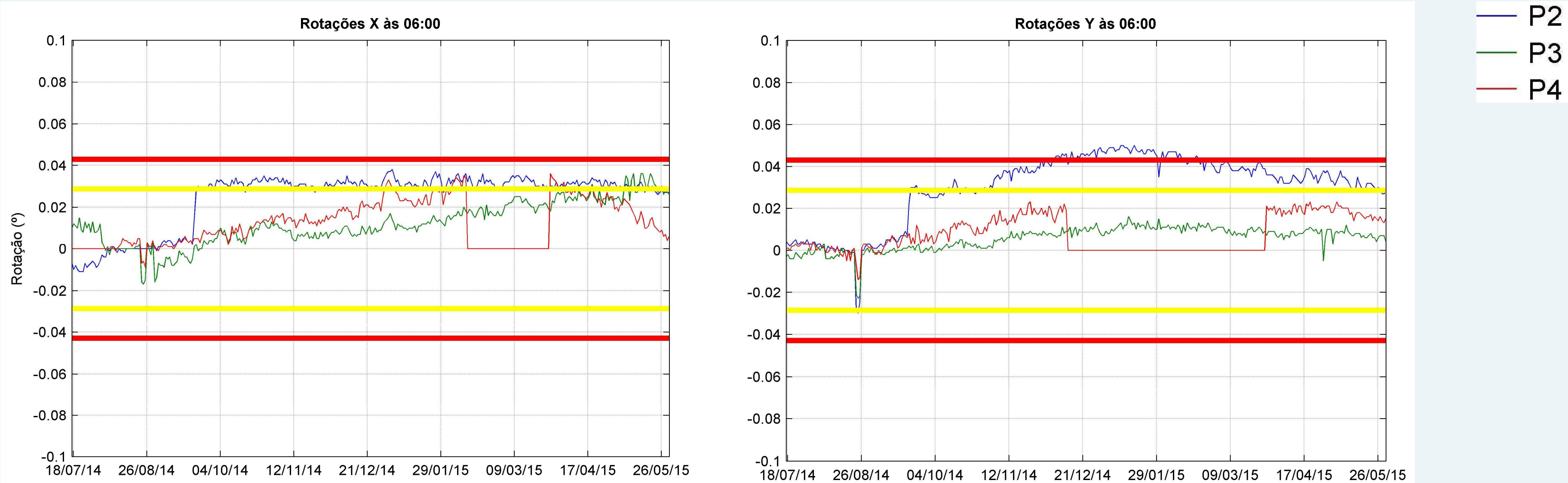


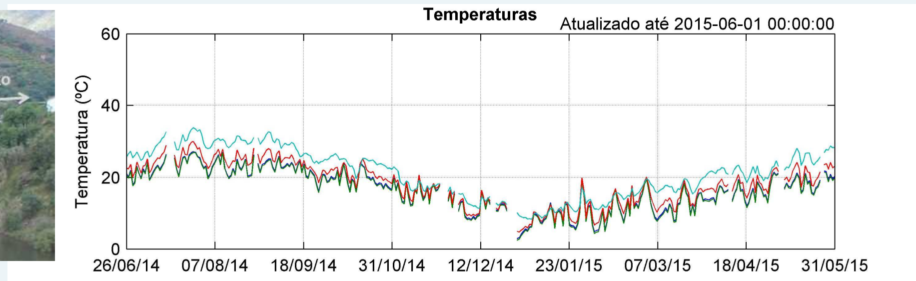
Increase of the first natural frequency after retrofit



Results - Railway Bridge

Clinometers

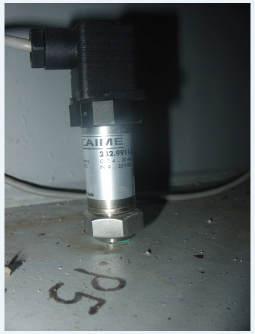




Continuous Aerodynamic Monitoring of "Viaduc de La Grande Ravine"

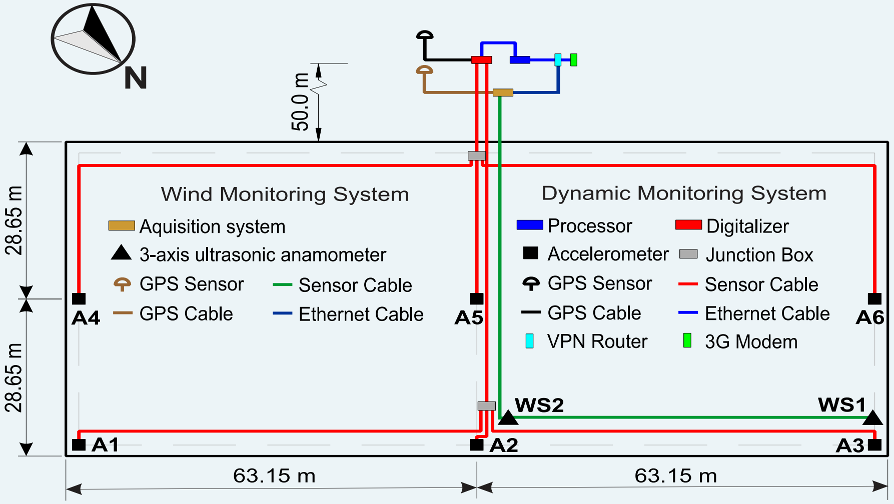
Continuous Aerodynamic Monitoring of "Viaduc de La Grande Ravine"

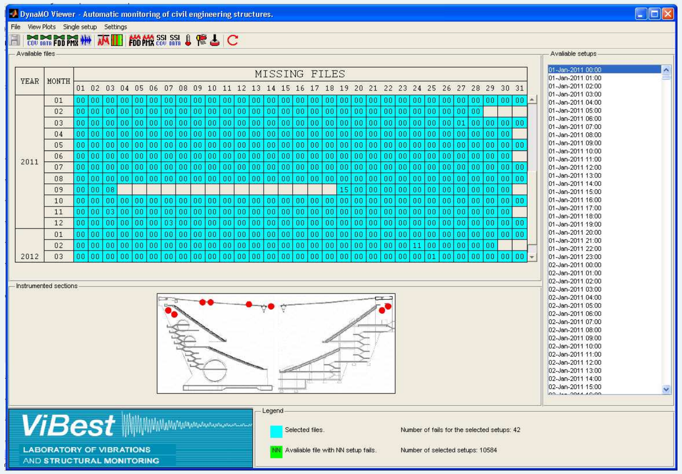


- 5 anemometers
- 14 pressure cells
- 6 termometers
- 6 accelerometers


Continuous wind and dynamic monitoring systems





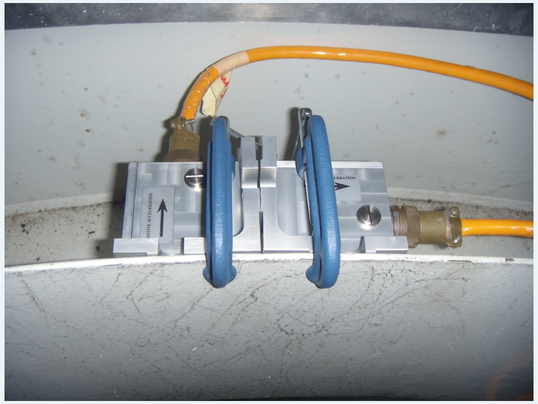
- 6 force balance accelerometers
- 2 sonic anemometers
- 8 temperature sensors
- Continuous sampling at 20 Hz/ 10Hz
- Records with 30 minutes duration
- Data transfer to a server at FEUP

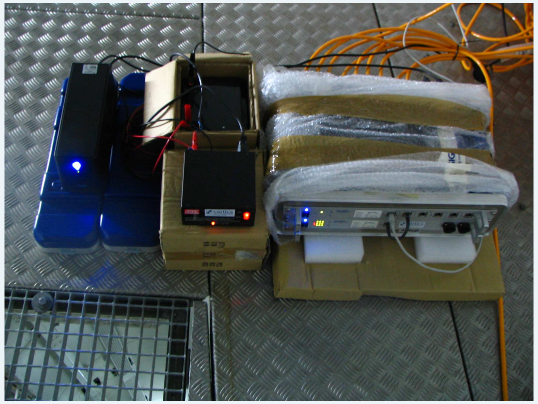
Active since March 2009

Wind Turbine

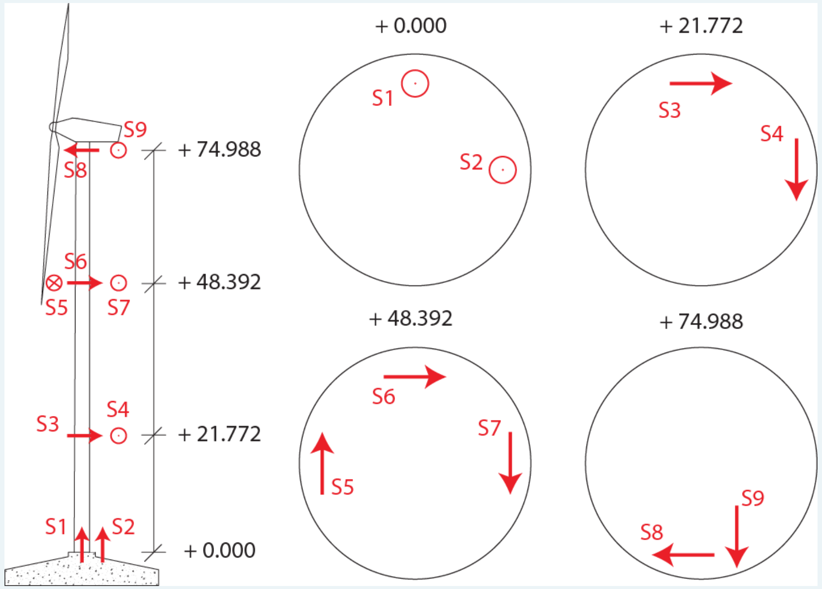
- Located in the North of Portugal (Torrão Wind Farm)
- 2.0 MW – variable speed generator
- Hub height: 80 m
- Rotor diameter: 80 m
- Tubular steel tower
- Bolted flanged connection between tower segments
- Slab foundation

Wind Turbine



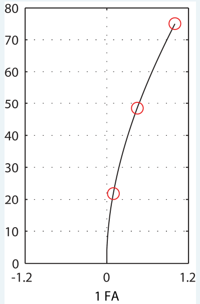


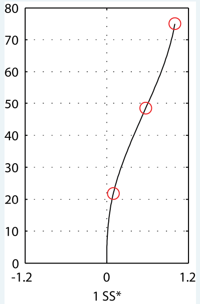
- **Monitoring system**
  - 9 accelerometers along 4 levels
  - 24-bit digitizer and acquisition system
  - Setups of 10 min. (accelerations + SCADA)

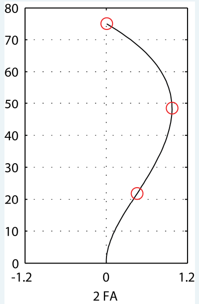


Automated Modal Tracking

- **Reference properties from 6 operating regimes**

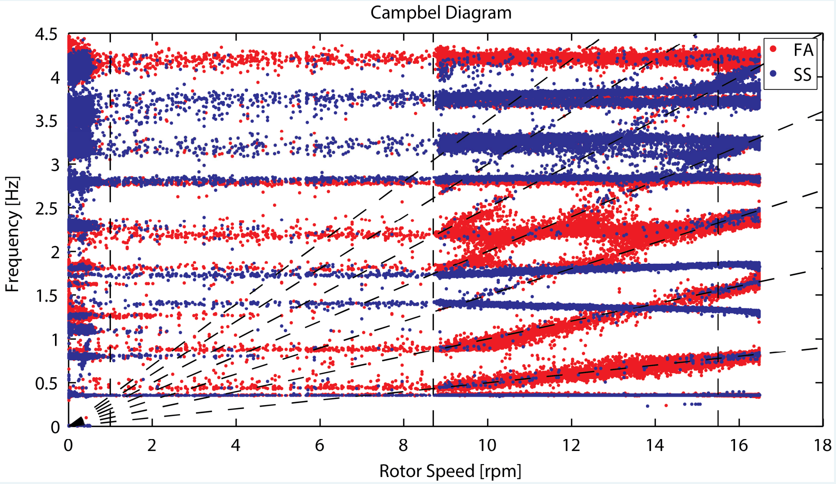


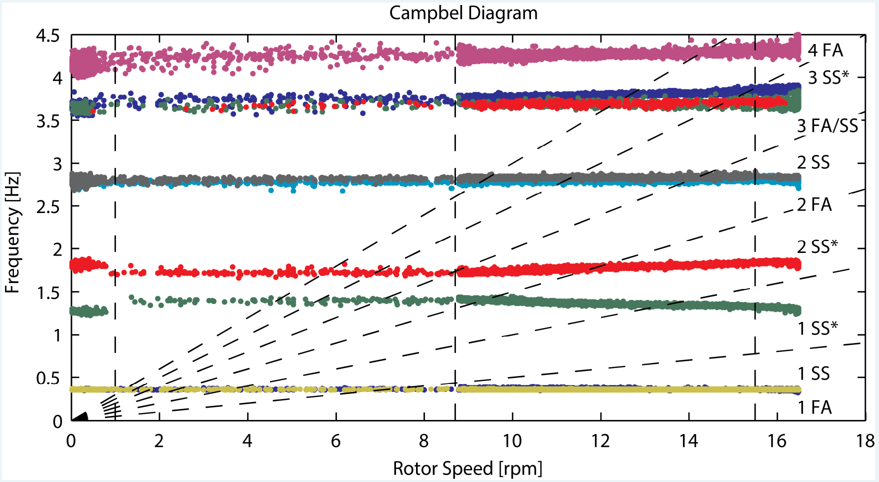




...

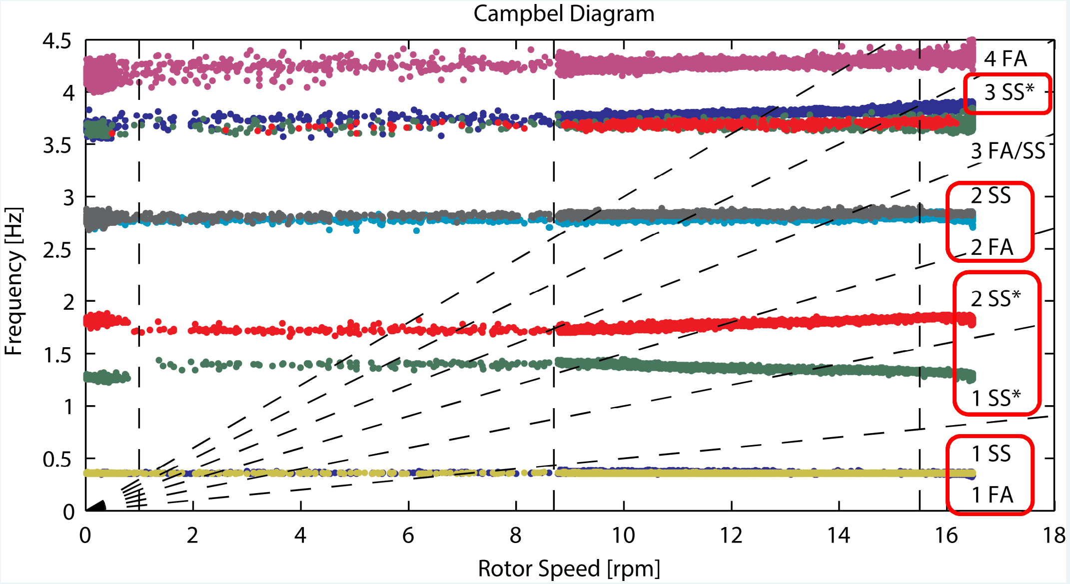
Operating regime	Wind turbine condition
1	Parked or idling (with high pitch angle)
2	Parked or idling (with lower pitch angle, in conditions to start operating)
3	Transition situation from non-operation to operation (mean value of rotor speed between 0 and the lowest operating rotor speed)
4	Between lowest operating rotor speed and the point where the pitch angle starts to increase to avoid excessive rotor torque values
5	Between regime 4 and highest operating rotor speed
6	Wind speed higher than cut-out speed

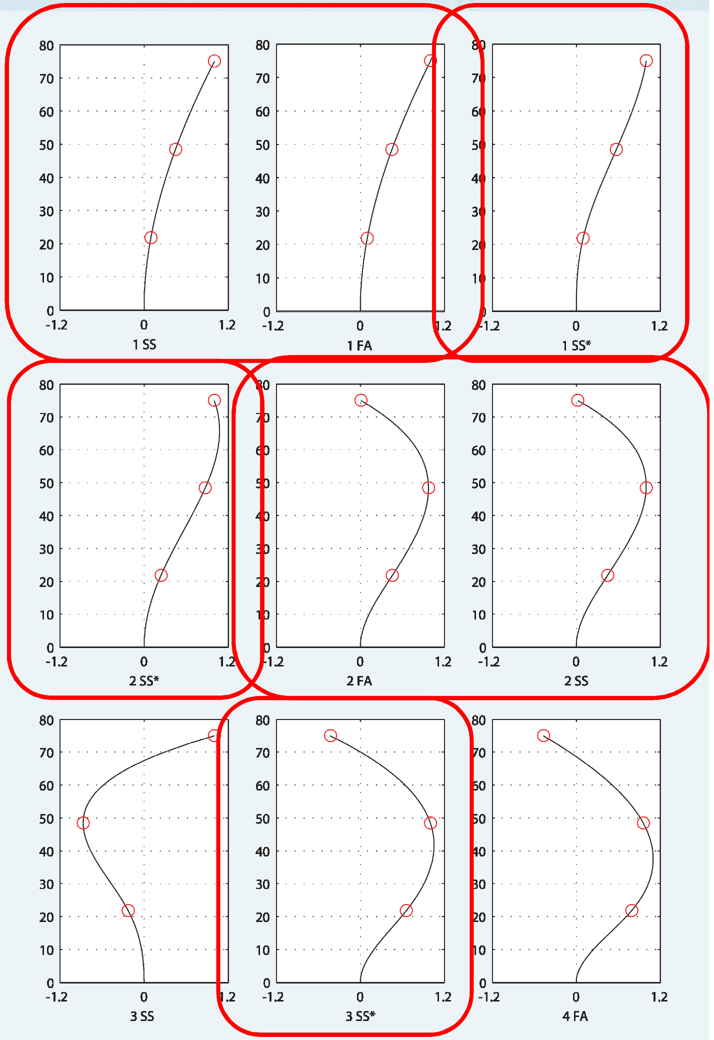




Automated Modal Tracking

- 9 vibration modes identified along the whole operating regime of the turbine

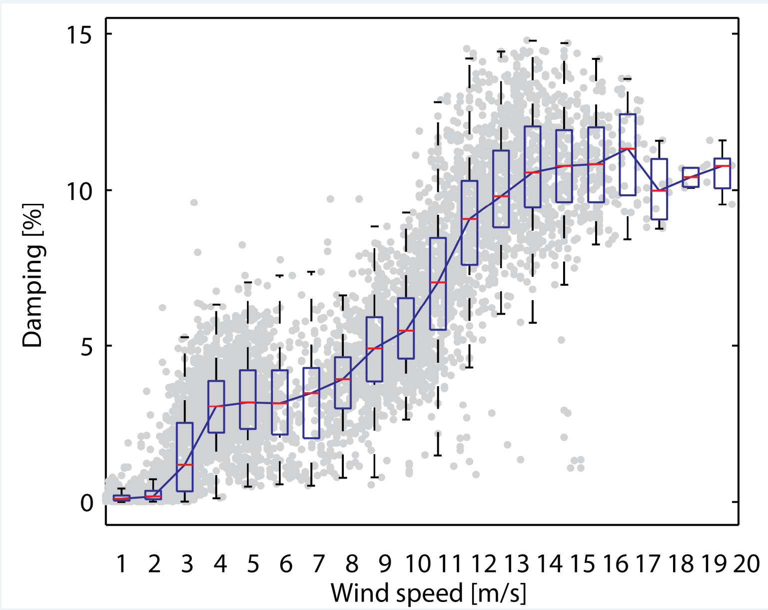




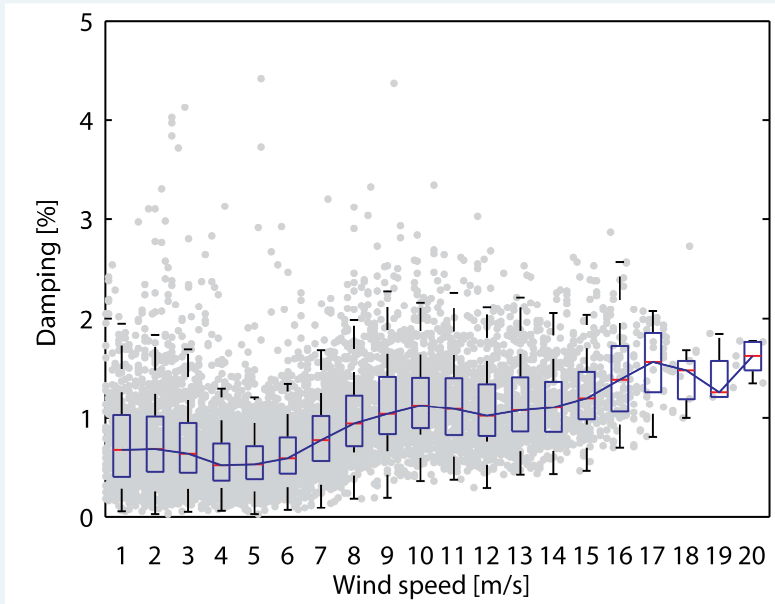
Automated Modal Tracking

- **Assessment of the modal properties at operating condition**
  - **Evolution of damping with the wind speed**

1st FA tower mode

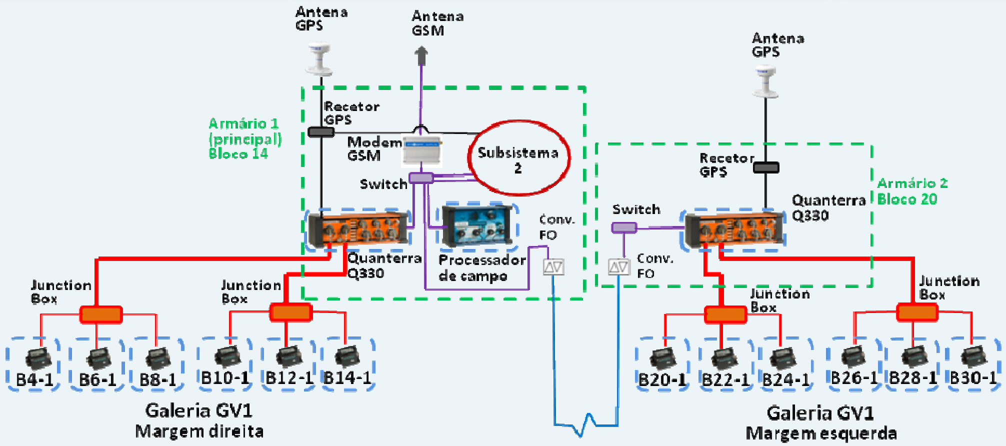


1st SS tower bending mode

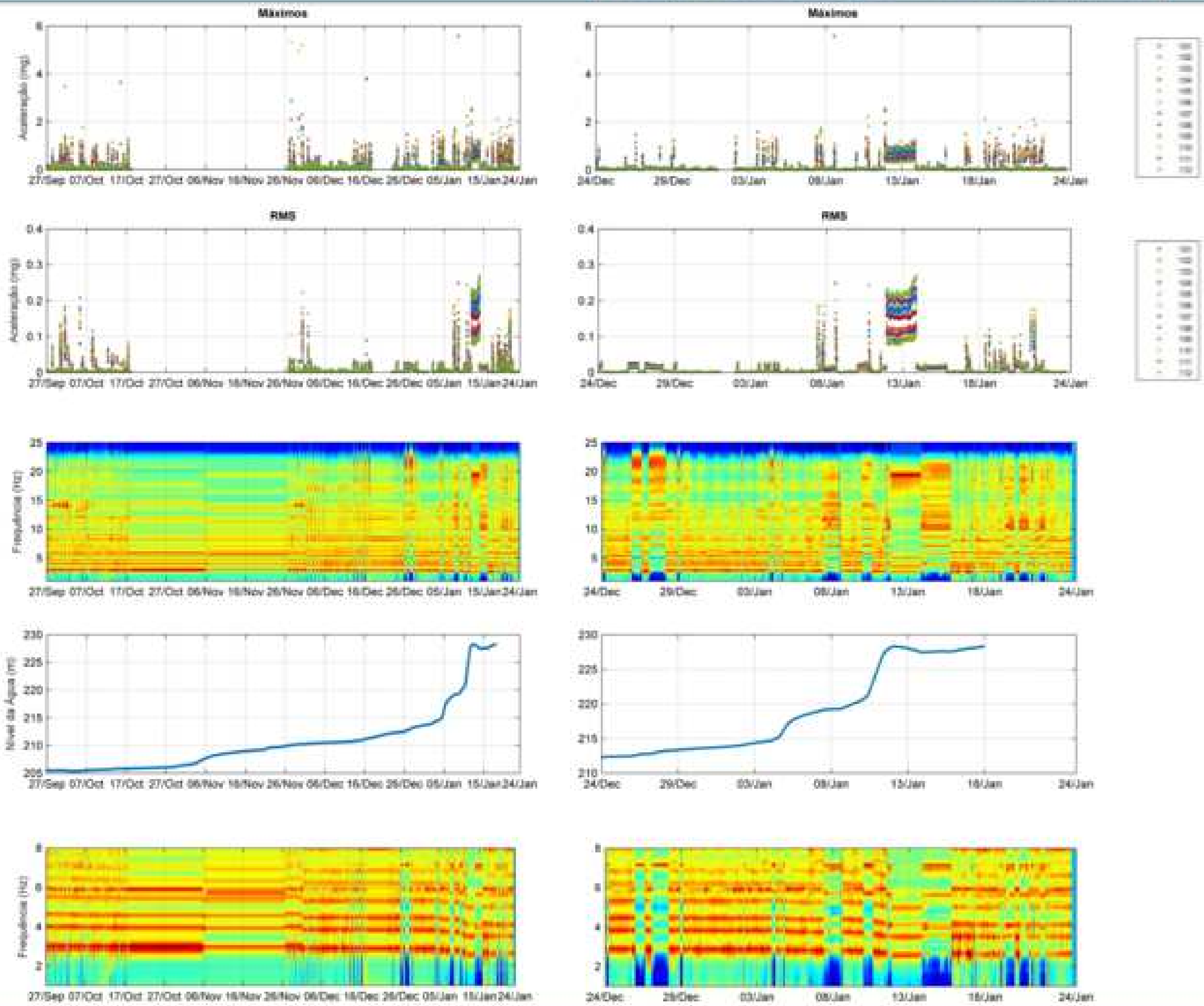


Dynamic Monitoring of Baixo Sabor Dam

- **Baixo Sabor Dam (Client: EDP)**



Sistema de Monitorização Dinâmica da Barragem do Sabor Escalão de Montante



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Conclusions

- The case studies previously described clearly show the usefulness and potential of continuous dynamic monitoring in large Civil structures of different typology (e.g. roadway, railway and pedestrian bridges, stadia suspension roofs, wind turbines or dams), provided that appropriate monitoring equipment and automated data processing tools are implemented
- ViBest_SHM is a very large digital data repository and information system that may be used for collaborative research at European level in the area of SHM

Laboratory of Vibrations and Monitoring

www.fe.up.pt/vibest