STRUCTURAL HEALTH MONITORING OF BRIDGES

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Experimental Methods in Civil Engineering
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Outline

- General overview
- LNEC's experience in Structural Health Monitoring of Bridges
- Bridges load testing
- New challenges
- Final remarks

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General overview

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Introduction

All structures, including bridges, **deteriorate with time**, due to various reasons including effects of environmental elements, fatigue failure caused by repetitive traffic loads, and extreme events such as an earthquake.

If the damages remain undetected, they will get worse and the structure may have a reduced margin of safety or have serviceability problem, increasing the risk of collapse increases, involving loss of life and property.

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Bridges inspections

Current damage detection methods are mainly based on visual inspections.

These inspections are essential for bridge management, but they have some limitations since they can only detect damage on or near the structure surface, as well large as displacements.

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Monitoring

Monitoring is the periodic and organized collection of information, followed by a systematic analysis of this information.

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Structural Health Monitoring

Structural Health Monitoring (SHM) is the verification of the performance of the structures in service, based on the measurement of relevant quantities, through sensors of different technologies, which provide significant information on the state of the structure.

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Structural Health Monitoring

Structural health monitoring involves the observation of a structure over a period using periodically spaced measurements, the extraction of features from these measurements, and the analysis of these features to determine the current state of health of the structural system.

The output of this process is periodically updated information regarding the ability of the structure to continue to perform its desired function considering the inevitable aging and degradation resulting from the operational environments.

Based on the monitored state, appropriate repair, rehabilitate, and/or strengthening of structures are decided to keep these structures operational and further to lengthen their lives.

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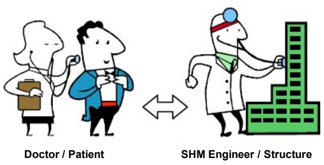
Structural Health Monitoring



in ISIS Canada Educational Module nº 5: *An Introduction to Structural Health Monitoring*, 2004

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Structural Health Monitoring: objective

Contribute to the safety, functionality and durability of the structure, as well to the optimization of its management through its useful life.

Through:

- Verification of structural behavior
- Early detection of structural damages
- Obtaining reference states
- Quantification of actions

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Situations where SHM is most relevant

- Structures with **innovative** structural solutions, materials or processes
- **Critical structures**, due to their economic or social importance
- Structures with significant **uncertainties** regarding geotechnical conditions, seismic risk, environmental aggressiveness or vulnerability during construction
- **Damaged structures**, whose condition raises doubts
- **Standard structures**

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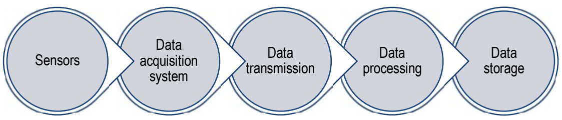
Composition of a SHM System



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Design of a Structural Health Monitoring system

- Definition of objectives
- Identification of the critical points of the structure
- Selection of the approach:
  - static / dynamic
  - local / global
  - permanent / temporary
  - periodic / continuous measurements
- Selection of sensors
- Selection of data acquisition and communication systems

Taking into account environmental, structural and budget restrictions

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Main measurements

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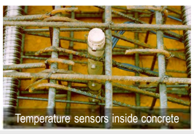
Weather parameters

- Temperature
- Relative humidity
- Wind (direction & speed)
- Rainfall


Temperature sensors inside concrete


Multi-Parameter Weather Sensor

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On-site study of the time-dependent behaviour of concrete

Strain gauges inside specimens | Specimens concreting | Creep and shrinkage specimens

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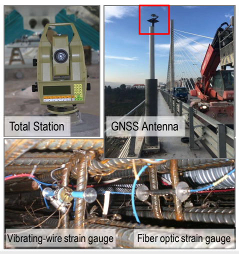
Monitoring of structural behaviour

Static behaviour
- Linear displacements
- Rotations
- Strains
- Movements of joints
- Forces in cables
- Support reactions



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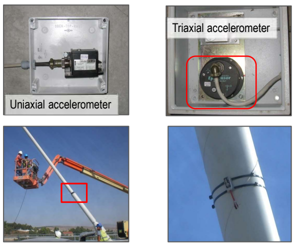
Monitoring of structural behaviour

Dynamic behaviour
- Accelerations



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Durability Monitoring

It has the purpose of early detect the development of favourable conditions to the corrosion of reinforcement bars and, thus, trigger mitigating measures.

Based on a set of measurements:
- Corrosion potential
- Galvanic current
- Electrical resistance
- Temperature

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Data acquisition

- A transducer sensor converts temperature, pressure, level, length, position, etc. into voltage, current, frequency, pulses or other signals.
- Signal conditioning circuits improve the quality of signals generated by sensors before they are converted into digital signals by the PC's data-acquisition hardware (signal scaling, amplification, linearization, filtering, etc.).
- Analog to digital conversion (A/D) changes analog voltage or current levels into digital information. The conversion is required to enable the computer to process or store the signals.

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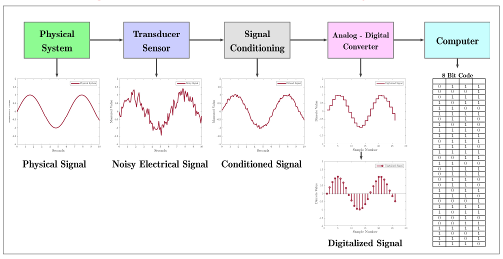
Digital data acquisition system



Risanuri Hidayat, *Data Acquisition*. http://paginas.fisica.uson.mx/horacio.munguia/aula_virtual/Cursos/Instrumentacion%20II/Documentos/Tutorial%20DAQ.ppt

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Criteria for choosing a data acquisition system

The most significant criteria are:

1. Number of input channels
2. Single-ended or differential input signals
3. Sampling rate (in samples per second)
4. Resolution (usually measured in bits of resolution)
5. Input range (specified in full-scale volts)
6. Noise and nonlinearity

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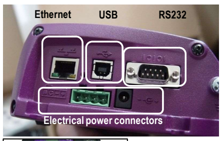
Data acquisition systems

Communication and power supply



www.datataker.com/

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SIGNAL ACQUSITION: THE MEASUREMENT AND I/O LEVEL

e.bloxx

The reliable measurement module

The e.bloxx modules acquire sensor and process signals with precision, speed and stability. To ensure durability the inputs, the power supply, and the interface ports are all galvanically isolated from each other. The industrial design reduces EMC and temperature influences to a minimum. We guarantee that our modules meet all specifications over a temperature range of -20°C to +60°C.

https://www.gantner.com/

e.bloxx Module
INPUT TYPES
Voltage
Current
Resistance
Pt100, Pt1000
Potentiometer
Thermocouple
Cryo Sensor
Single Strain Gage
Half Bridge Strain Gage
Full Bridge Strain Gage
Inductive Half Bridge
Inductive Full Bridge
LVDT
ICP Sensor
Frequency Signal
Pulse Width
Counter
Status
CAN Data
Serial Sensors, SSI

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SIGNAL CONDITIONING: THE CONTROLLER LEVEL

Test Controller
HOST INTERFACES
Ethernet TCP/IP
Profibus-DP (12Mbps)
EtherCAT
USB 2.0
CANopen
RS-232
RS-485
SLAVE INTERFACES
RS-485 Localbus
RS-485 variable
SDI-12
DATA STORAGE
16 MB RAM
128 MB Flash
USB expandable

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Inspeção, ensaios e monitorização

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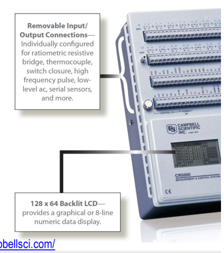
Data acquisition systems



Design Features

- Stand-alone unit offering high performance and an environmentally rugged design
- Maximum throughput of 2k to 5k measurements per second (configuration dependant)
- Powerful instruction set that supports measurement of most sensor types, on-board processing, data reduction, and intelligent control
- Backlit display allowing numerical or graphical display of stored data
- PCMCIA card slot for extended data storage and transporting data to a PC
- Battery-backed SRAM memory and clock ensuring data, programs, and accurate time are maintained while the CR5000 is disconnected from its main power source
- Robust ESD protection
- Low power, 12 Vdc operation
- Data values stored in tables with a time stamp and record number

https://www.campbellsci.com/

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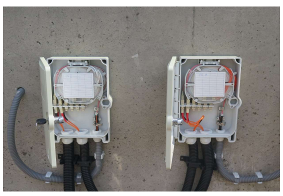
Data transmission

- In a monitoring system in which several quantities are to be measured, with various acquisition equipment distributed throughout the structure, its interconnection and data centralization in a local server is indispensable.
- For this purpose, a communication LAN must be installed which can use, for example, RS485 type protocols or an Ethernet type network.
- This network can be fiber optic cable, which provides the best performance in speed and transmission quality.



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Data transmission

Data acquired by a local acquisition system can be transmitted to a server located outside the work site through a fixed communication network of the Internet type or using mobile communication operators, through communication protocols of the type:

- *GPRS - General Packet Rádio Service*
- *HSDPA - High-Speed Downlink Packet Access (3.5G)*
- *4G: fourth generation of broadband cellular network technology*

Router HSDPA

Modem/Router 3G/4G/WiFi online

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Advantages of a DAQ

- Continuous Acquisition
- Simultaneous Acquisition
- No operator presence
- Remote access
- Alarm Setting

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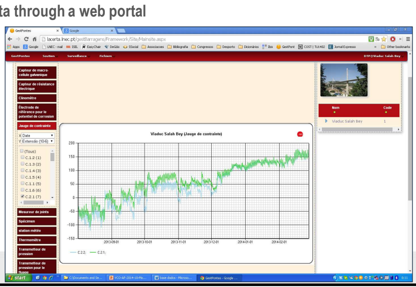
Data management

Access to data through a web portal



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LNEC's experience in Structural Health Monitoring of Bridges

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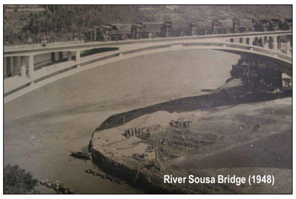
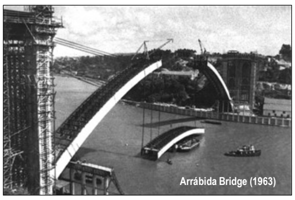
In the early years

River Sousa Bridge (1948)



Arrábida Bridge (1963)



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In the early years

Tagus river suspension bridge (1966)

- Main issue: safety
- Necessity to design equipment
- Numerical models had low capacity

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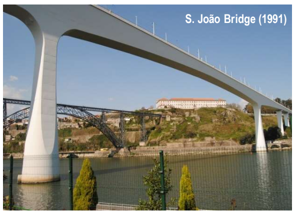
Current situation

Bridge SHM systems set-up by LNEC

- Total: 19 (15 proactive; 4 reactive)
- Type of monitoring:
  - Static (17)
  - Dynamic (5)
  - Durability (4)
- Long-term records of data
- Old systems have been upgraded



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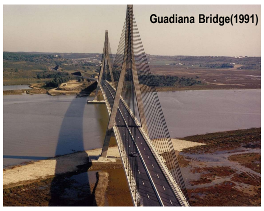

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Current situation

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Current situation

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Current situation

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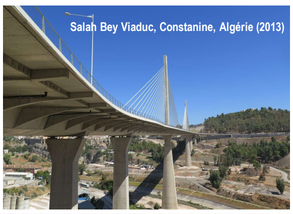
Current situation



Ribeira d'Água Bridge, Boavista Island, Cabo Verde (2015)

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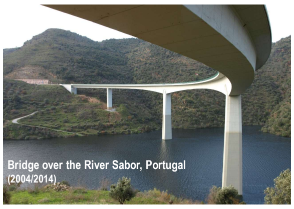
Current situation



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Bridges load testing

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Bridges load testing

- **Static load testing**
  - They aim to assess the behaviour of a structure when subjected to significant loads
- **Dynamic testing**
  - They aim to to obtain the main frequencies, the associated modal shapes, and the damping ratios.

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Static load testing

- **Destructive testing**
  - Collection of information for research purposes
  - Bridges whose demolition is decided
- **Proving load testing**
  - Aim to provide a realistic evaluation of the safe load-carrying capacity of a structure
  - Load is applied in increments to some pre-set maximum or until the structure shows signs of deterioration
- **Proof loading**
  - It is intended to show that the design and construction have been carried out in a satisfactory manner
  - Level of loading is equivalent to the level of loading specified for the serviceability limit state
- **Supplementary load tests**
  - Are intend to supplement the analytical methods of assessment based on calculation
  - The levels of loading are such that they will be sufficient to obtain satisfactory measurable responses from the structure concerned without causing any permanent structural damage

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Static load testing

Proof loading

Bridge over Sado river, Alcácer, Portugal

17 de Setembro Bridge, Cabala, Angola

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Static load testing

Supplementary load tests

Ramalho Ortigão Viaduct, Lisboa, Portugal

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Dynamic testing

Forced vibration tests

Based on the response of a structure to a continuous forcing function that causes the structure to vibrate at the frequency of the excitation.

A hydraulic or a mechanical vibrator was used to artificially excite the bridge.

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Dynamic testing

Free-vibration tests

Based on the natural response of a structure to some impact or displacement. The response is completely determined by the properties of the structure, and its vibration can be understood by examining the structure's mechanical properties.

Particularly suitable for the **determination of damping coefficients**

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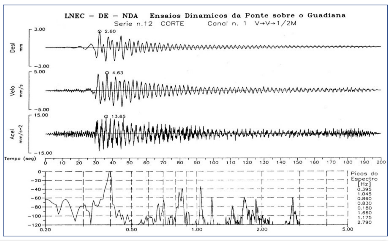
Dynamic testing

Free-vibration tests



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Dynamic testing

Free-vibration tests

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Dynamic testing

Ambient vibration testing

- Tests performed with ambient vibration only, like wind or traffic.
- High sensitivity equipment required, as structure response amplitudes can be low.
- Non-intrusive

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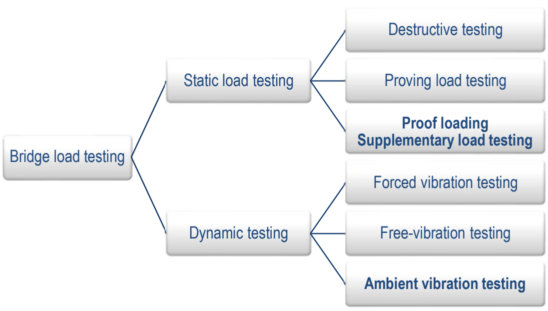

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New challenges

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Main SHM challenges

- Monitoring the effects of material degradation
- Development of techniques for damage identification
- Use of low-cost sensors (testing reliability, durability, etc.)
- Integration of SHM into bridge management systems
- Quantification of the value of SHM information

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Monitoring the effects of material degradation

Main degradation mechanisms

- Fatigue
- Corrosion
- Swelling reactions of concrete

SHM usefulness

- Assessment of safety conditions
- Calibration of degradation models
- Selection of mitigating measures
- Validation of the effectiveness of the measures adopted

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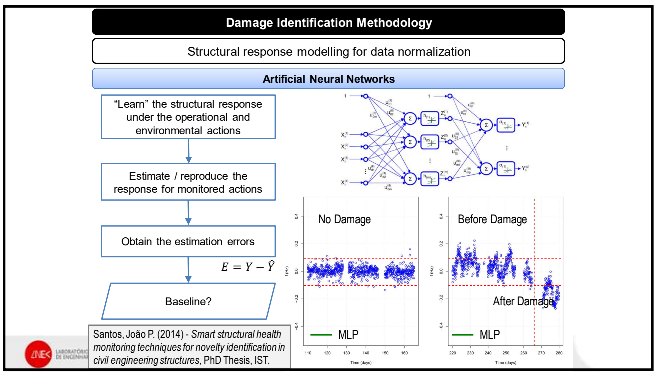

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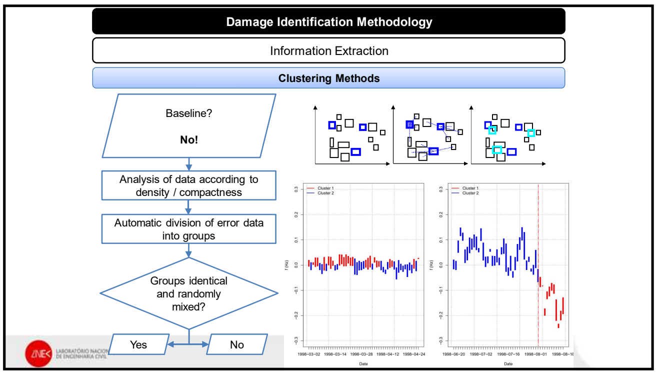

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Low cost sensors

MEMS

Micro-electromechanical systems (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometres to millimetres. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

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Quantification of the value of SHM information

- **Costs:** perfectly determined
- **Benefits:** generally recognized, but how to quantify ?
- **Cost-benefit analysis**: useful for bridge owners and for SHM system design

COST Action TU1402: *Quantifying the value of structural health monitoring*

- The Value of Information (VoI) is a decision analytic method for quantifying the potential benefit of additional information in the face of uncertainty.
- Bayesian decision making involves basing decisions on the probability of a successful outcome, where this probability is informed by both prior information and new evidence the decision maker obtains

http://www.cost-tu1402.eu/

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Final remarks

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Key benefits of SHM

- Better knowledge of the structural behaviour
- Early damage detection
- Increasing structural safety
- Improving the planning of maintenance and conservation
- Longer lifespans
- Cost efficiency

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LNEC's experience

LNEC has an extensive practice in bridge testing and monitoring

- Significant benefits have been achieved
- Good communication between bridge owners and SHM experts
- The data collected has a high potential for research

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Main SHM challenges

- Monitoring the effects of material degradation
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