STRUCTURAL HEALTH MONITORING (SHM)

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REFERENCES

- SHM http://www.shmlive.com/
- SAMCO http://www.samco.org/network/index.htm
- ISIS and SAMCO Educational Module 5: An Introduction to Structural Health Monitoring

- Population depends on an extensive infrastructure system
  - roads
  - highways
  - buildings
  - … etc
- The infrastructure system has suffered
  - neglect
  - deterioration
  - lack of funding
  - …

→ **Global Infrastructure Crisis**

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Example from USA

2005 Report Card for America's Infrastructure

Aviation	D+
Bridges	C
Dams	D
Drinking Water	D-
Energy	D
Hazardous Waste	D
Navigable Waterways	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D
Schools	D
Security	I
Solid Waste	C+
Transit	D+
Wastewater	D-

America's Infrastructure G.P.A. = D

Total Investment Needs = $1.6 Trillion (estimated 5 year need)

Click here for Grade Definitions

TABLE A ★ 2009 Report Card for America's Infrastructure

Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks and Recreation	C-
Rail	C-
Roads	D-
Schools	D
Solid Waste	C+
Transit	D
Wastewater	D-

AMERICA'S INFRASTRUCTURE G.P.A. **D**

ESTIMATED 5 YEAR INVESTMENT NEED **$2.2 TRILLION**

AMERICA'S INFRASTRUCTURE G.P.A. D+

SHARE PDF

Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety and resilience. METHODOLOGY >

AVIATION	D	PORTS	C
BRIDGES	C+	PUBLIC PARKS AND RECREATION	C-
DAMS	D	RAIL	C+
DRINKING WATER	D	ROADS	D
ENERGY	D+	SCHOOLS	D
HAZARDOUS WASTE	D	SOLID WASTE	B-
INLAND WATERWAYS	D-	TRANSIT	D
LEVEES	D-	WASTEWATER	D

A = Exceptional
B = Good
C = Mediocre
D = Poor
F = Failing

ESTIMATED INVESTMENT NEEDED BY 2020: $3.6 TRILLION

(3600 mil. USD)

Grade Definitions

A – Exceptional
B = Good
C = Mediocre
D – Poor
F – Failing
I = Incomplete

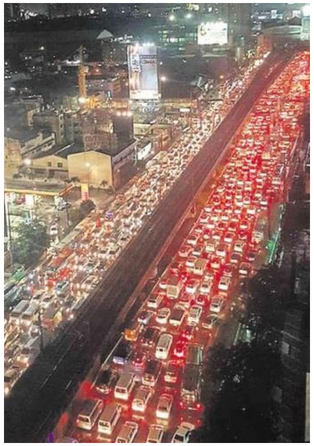
→ Global Infrastructure Crisis

• Factors leading to the extensive degradation

Factor 1 →**Unsatisfactory inspection and monitoring** of existing infrastructure

Consequences: → Problems become apparent only when structures are in dire need of repair

Result →**Repair costs become comparable to replacement costs**



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- Factors leading to the extensive degradation

Factor 2 → **Corrosion** of conventional steel reinforcement within concrete

Consequences: → Expansion of steel leads to cracking and spalling, further deterioration

Result → **Reductions in strength and serviceability, resulting in need for repair and/or replacement**

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- Factors leading to the extensive degradation

Factor 3 → **Increased loads** or **design requirements** over time (e.g. heavier trucks)

Consequences: → Increased deterioration due to overloads or to structural inadequacies resulting from design

Result → **Structures deemed unsafe or unserviceable and strengthening or replacement is required**

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- Factors leading to the extensive degradation

Factor 4 → Overall deterioration and/or **aging**

Consequences: → Various detrimental effects on structural performance, both safety and serviceability

Result → **Need for repair, rehabilitation, strengthening or replacement**

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SHM + **FRP**

→ New and innovative **materials** and **monitoring tools** that prolong the service lives of structures while decreasing costs

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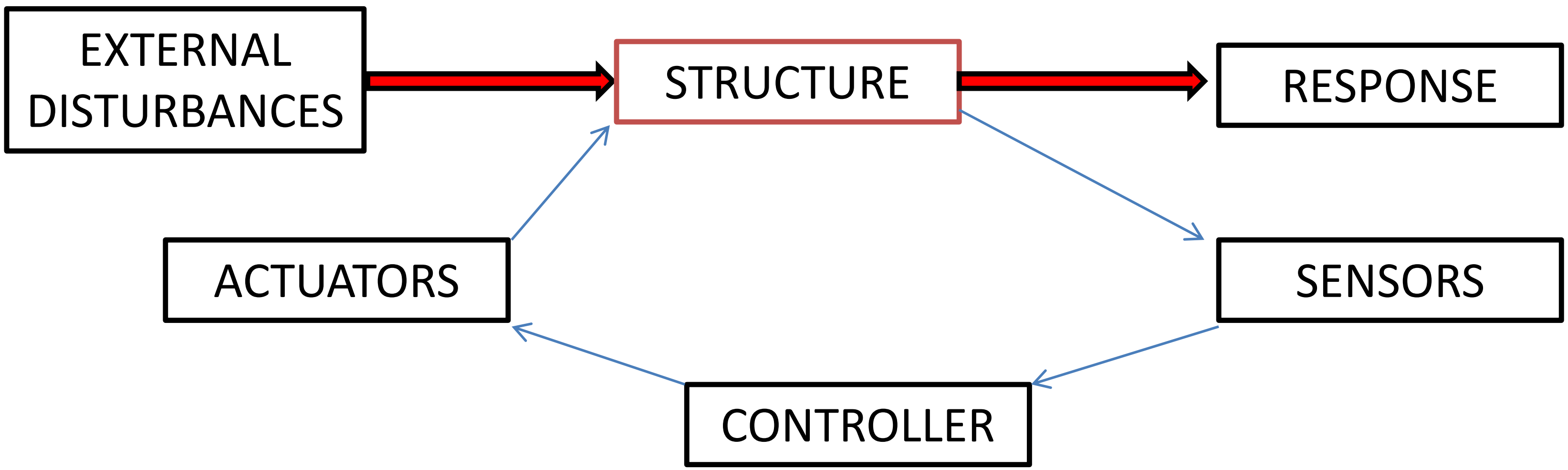
→ **Assessing** the in-service **performance** of structures using a variety of **measurement techniques**

→ Leading to "**smart**" structures



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→ **Assessing** the in-service **performance** of structures using a variety of **measurement techniques**

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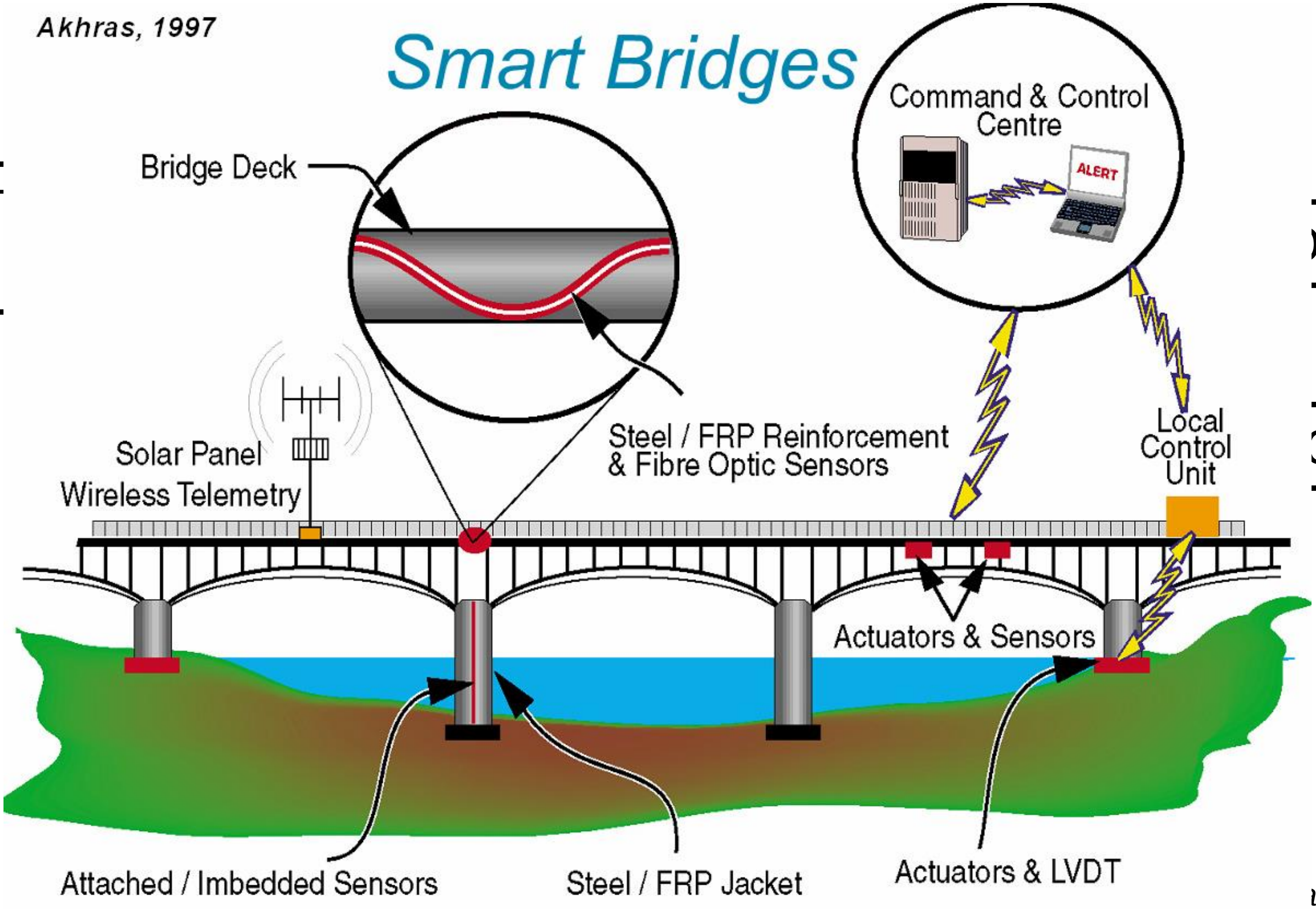

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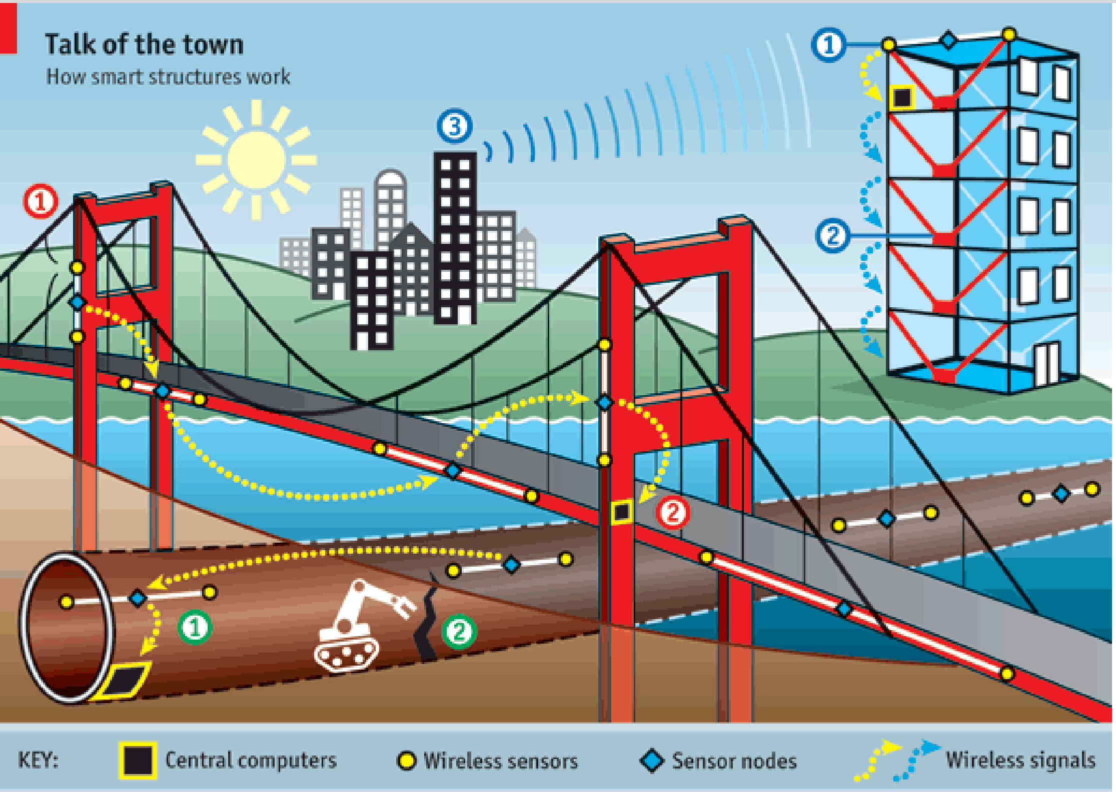
INTRODUCTION

Why we need SHM?



SMART BUILDING

1. Sensors in a building monitor the building's movement in response to strong winds or earthquake tremors.
2. Shock absorbers (hydraulic dampers) can then be made to stiffen or relax and heavy weights (mass dampers) can be moved to reduce oscillations in strong winds, or minimise damage in the event of an earthquake.
3. Buildings that detect an earthquake tremor could even warn other buildings nearby of the approach of a shockwave, so they could sound an alarm and prepare themselves accordingly.

SMART BRIDGE

1. Wireless sensors mounted on the bridge monitor vibrations, displacement and temperature. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem is detected, such as a loose bolt or cable, or the beginning of a crack, a warning can be sent by SMS.

SMART TUNNEL

1. Wireless sensors mounted on the walls of a tunnel monitor displacement, temperature and humidity. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem with the tunnel lining is detected, appropriate maintenance can be carried out. In future, a smart tunnel could even use robots to perform some maintenance tasks automatically.

www.economist.com

Inspection → On-site non-destructive examination to establish the present condition of the structure

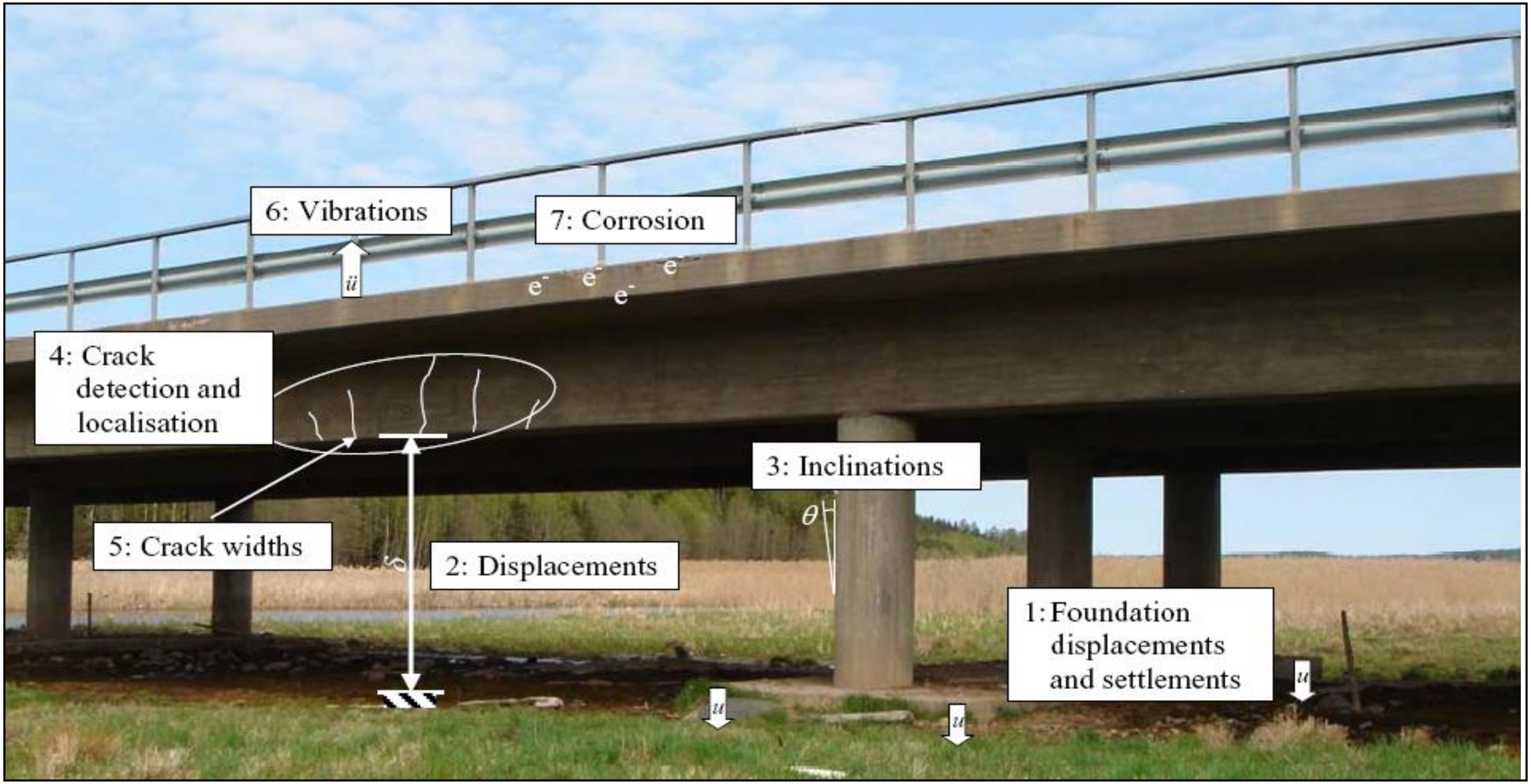
Load testing → Test of the structure or part thereof by loading to evaluate its behavior or properties, or to predict its load-bearing capacity

Monitoring → Frequent or continuous, normally long-term, observation or measurement of structural conditions or actions

Björn Täljsten

INTRODUCTION

Why we need SHM?



-follow up physical phenomenon
-check out the calculation models
-assessment of structures
-verification of the strengthening effects

Björn Täljsten

Emerging use of SHM is a result of:

1. The increasing need for
   - Monitoring of innovative designs and materials
   - Better management of existing structures

2. The ongoing development of
   - New sensors (e.g. Fiber Optic Sensors (FOS), “smart” materials etc.)
   - Data acquisition systems (DAS)
   - Wireless and internet technologies
   - Data transmission, collection, archiving and retrieval systems
   - Data processing and event identification

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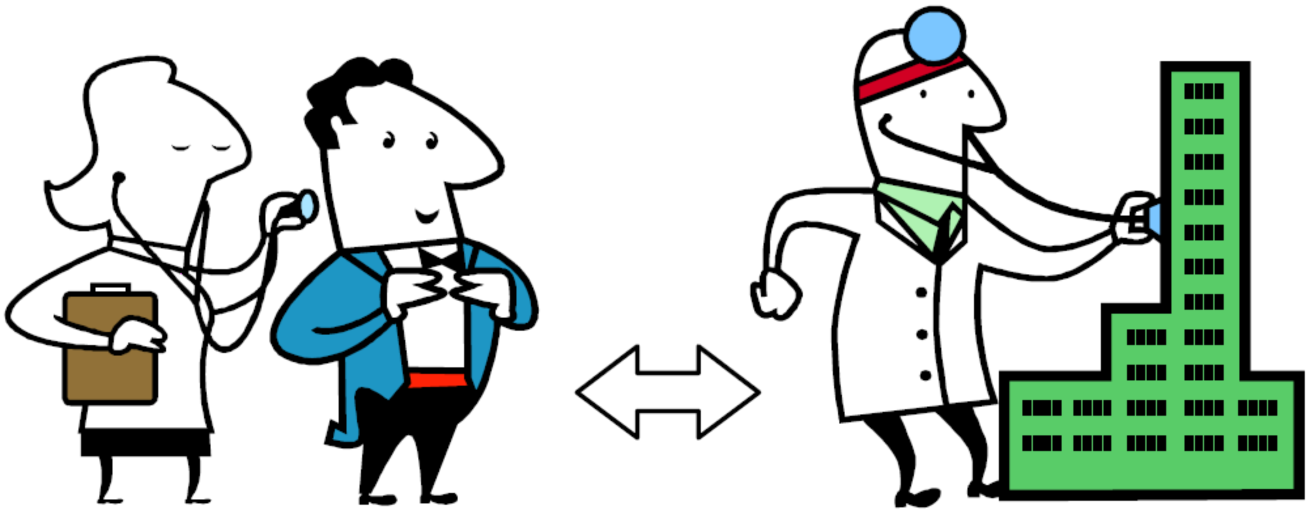
Medical Doctor

SHM Engineer



Medical Doctor

- Monitor patient's health
- Uses medical equipment to check overall health
- Prescribes corrective medicine if required

SHM Engineer

- Monitor condition of structures
- Uses sensors to check overall structural health
- If excessive stress or deformation, correct situation

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Acquisition of Data

↓

Communication of Data

↓

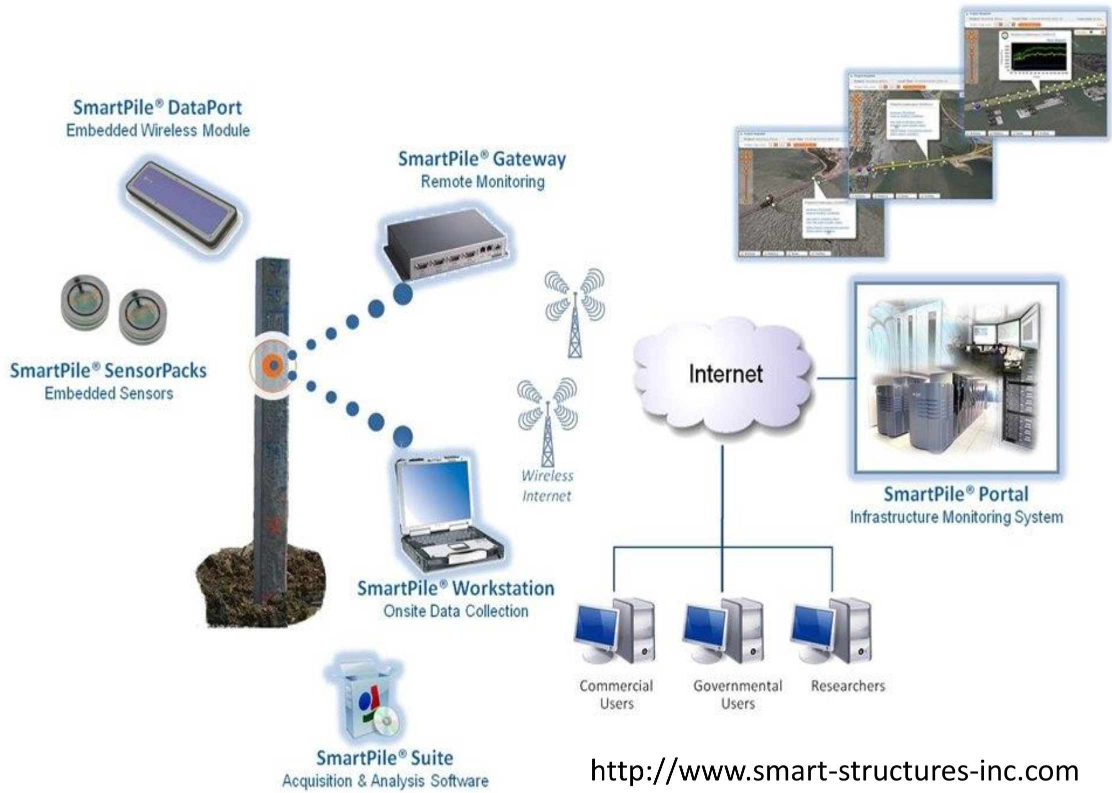
Intelligent Processing

↓

Storage of Processed Data → **Retrieval of Data**

↓ ↕

Diagnostics



http://www.smart-structures-inc.com

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Static Field Testing:
- Behaviour tests
- Diagnostic tests
- Proof tests

Dynamic Field Testing:
- Stress history tests
- Ambient vibration tests
- Dyn. Load Allowance (DLA) tests
- Pullback (anchored cables) tests

Periodic Monitoring:
- Field testing
- Tests to determine changes in structure

Continuous Monitoring:
- Active monitoring
- Passive monitoring

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Level IV
Detect presence, location, severity and consequences of damage

Level III
Detect presence, location and severity of damage

Level II
Detect presence and location of damage

Level I
Detect presence of damage

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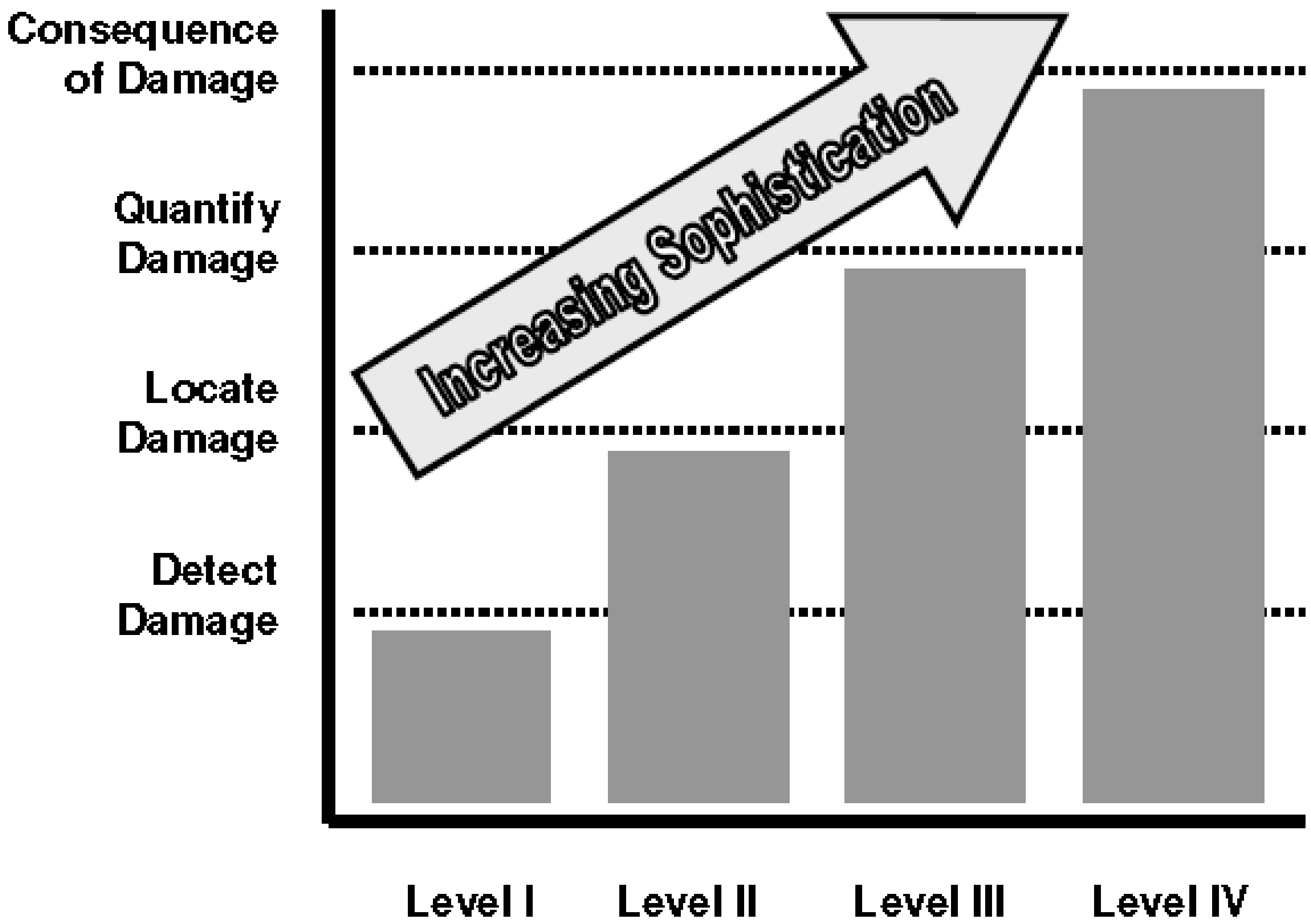
WHAT IS SHM?

Classification of SHM Systems



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Advantages of SHM

- Increased understanding of in-situ structural behaviour
- Early damage detection
- Assurances of structural strength and serviceability
- Decreased down time for inspection and repair
- Development of rational maintenance / management strategies
- Increased effectiveness in allocation of scarce resources
- Enables and encourages use of new and innovative materials

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METHODOLOGY

- Ideal SHM system:

    1. Information on demand about a structure's health
    2. Warnings regarding any damage detected

- Development of a SHM system involves utilizing information from many different engineering disciplines

    - Computers
    - Materials
    - Communication
    - Structures
    - Sensors
    - Damage Detection
    - Intelligent Processing
    - Data Collection

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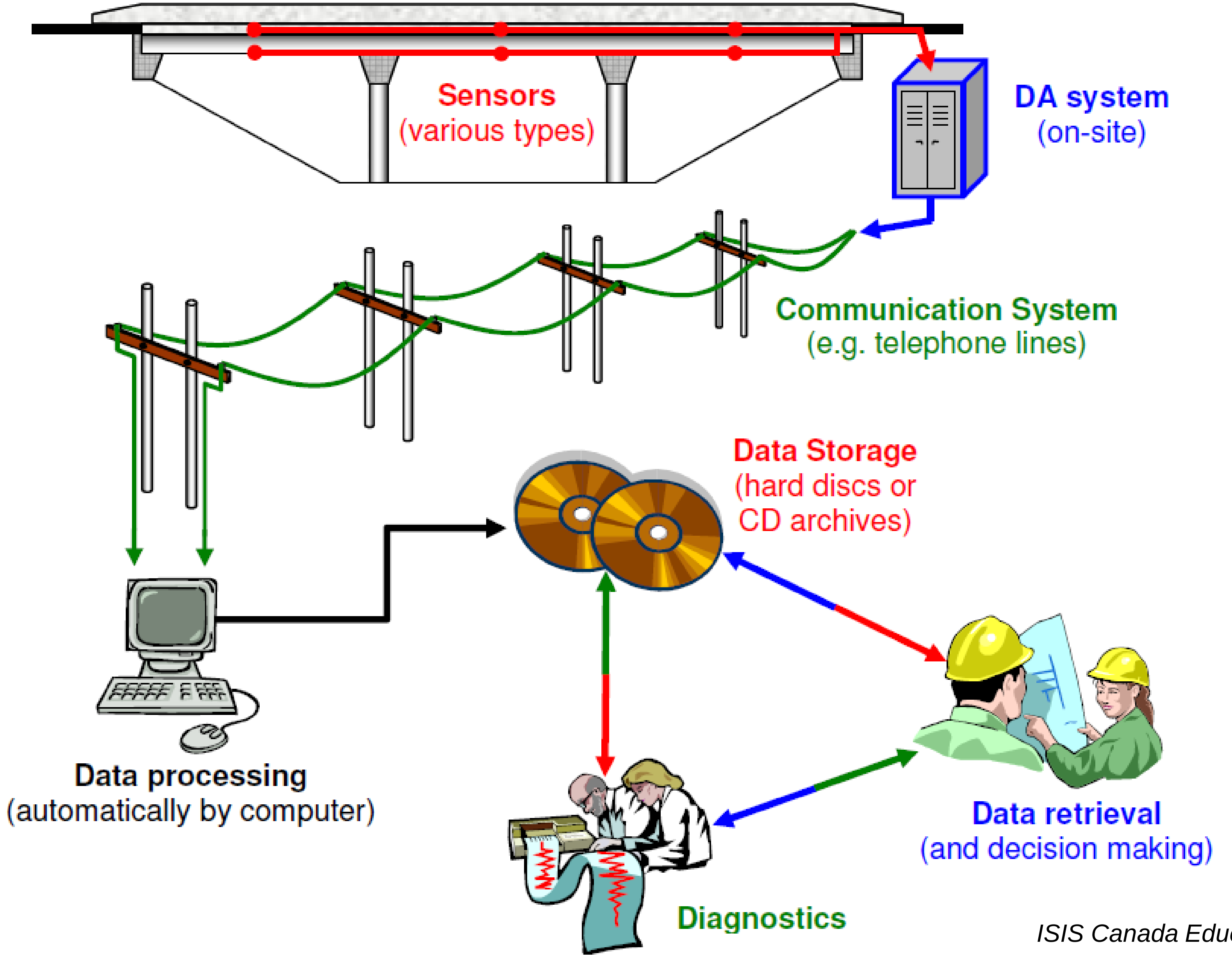
METHODOLOGY — System Components



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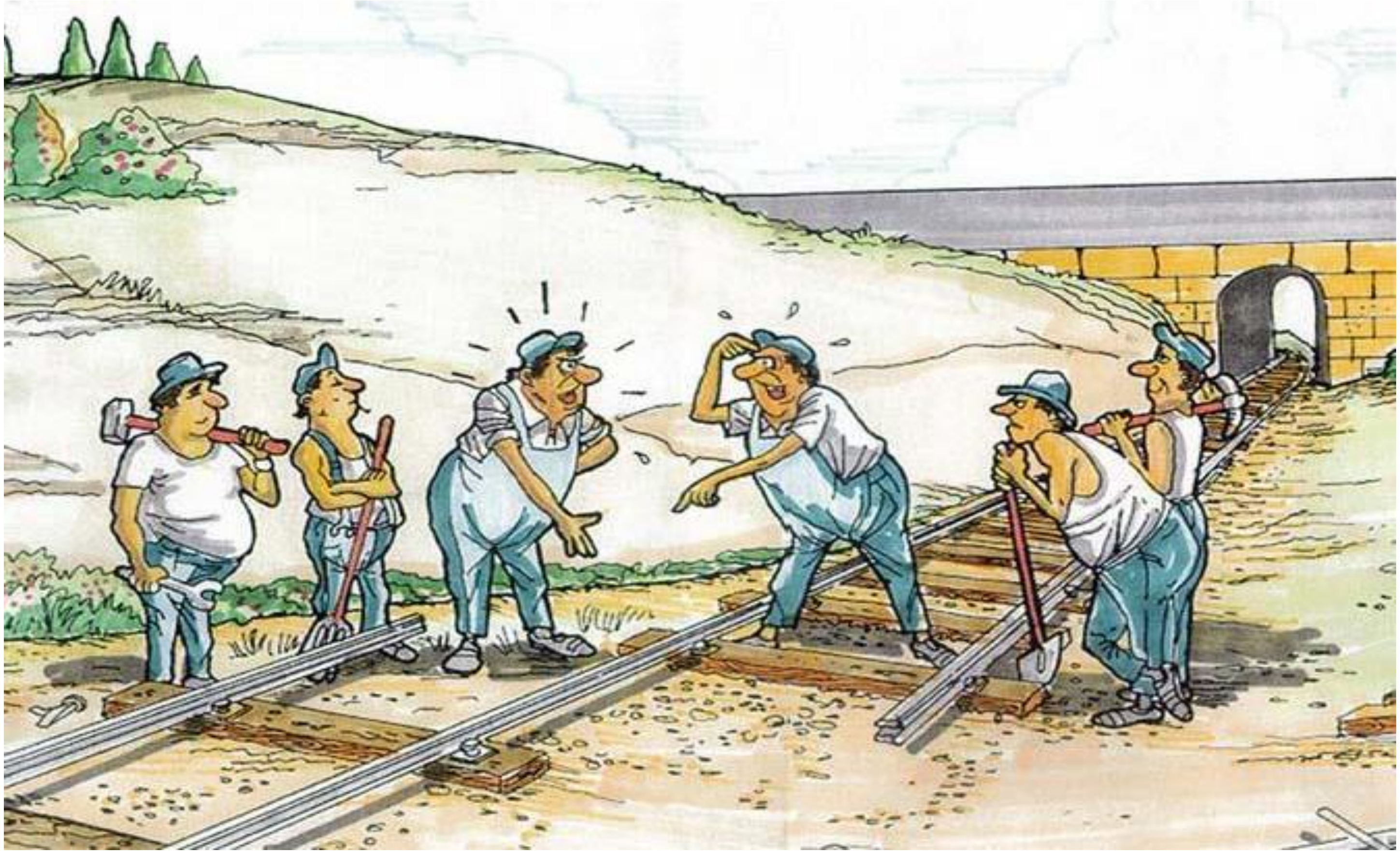
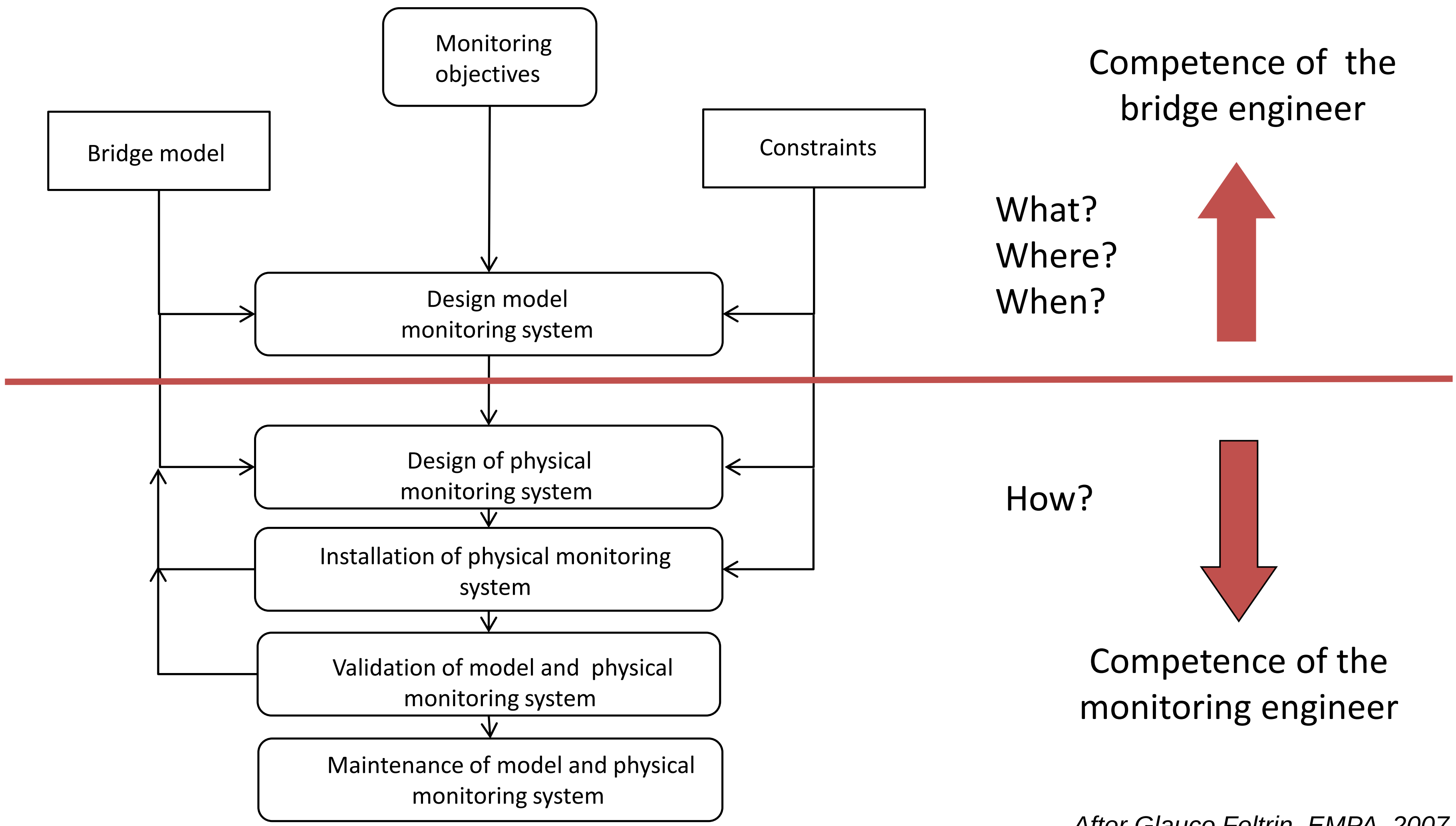
Basic Monitoring Methodology
→ Interdisciplinary Team Work

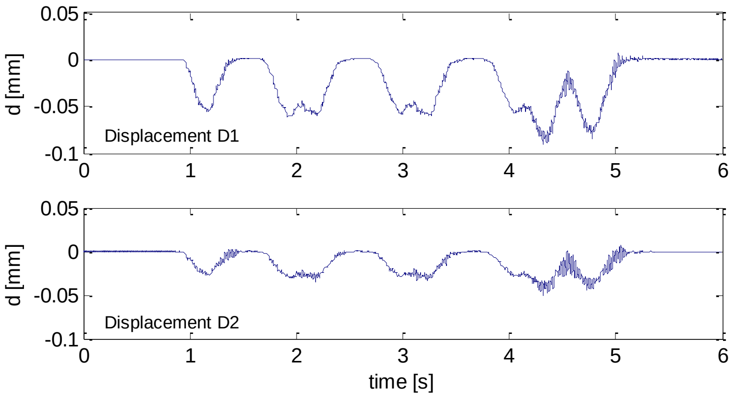


Basic Monitoring Methodology



After Glauco Feltrin, EMPA, 2007

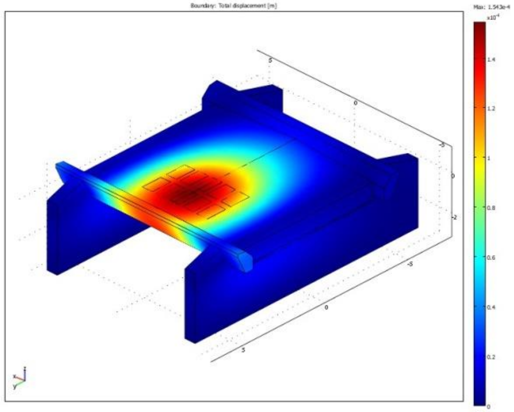
Monitoring Principles



Improved correlation

Interaction bridge model/monitoring

Do model results match with monitoring results?



Modification of model

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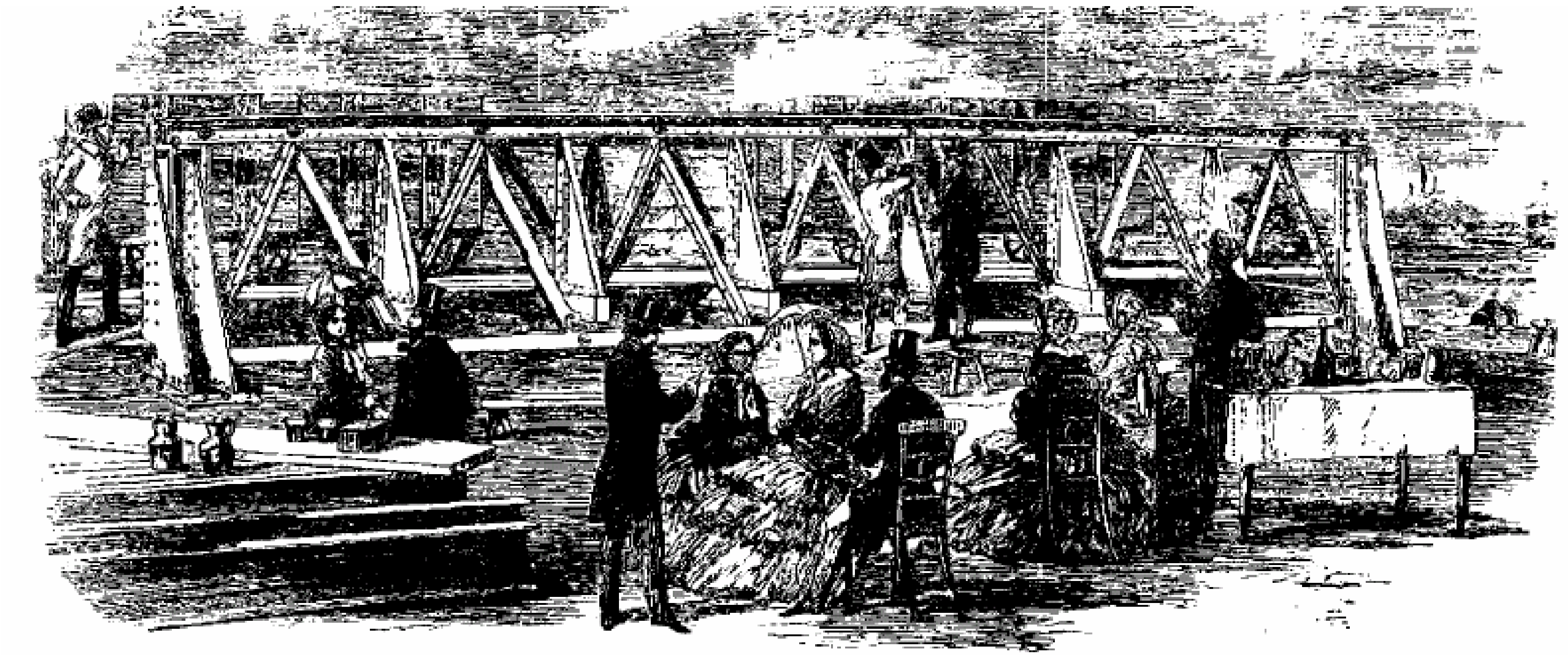
Monitoring

Verification by monitoring – not new



Testing of a steel truss in England for a railway bridge in India in the 19th century

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The collection of raw data: strains, deformations, accelerations, temperatures, moisture levels, acoustic emissions and loads

(a) Selection of Sensors

- Appropriate and robust sensors
- Long-term versus short-term monitoring
- What aspects of the structure will be monitored?
- Sensors must serve intended function for required duration

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(b) Sensor Installation and Placement

- Must be able to install sensors without altering the behaviour of the structure

- Features such as sensor wiring, conduit, junction boxes and other accessories must be accounted for in the initial structural design

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(c) Transfer to Data Acquisition System (DAS)

- **Method 1 - Lead wire**
  - direct physical link between sensor and DAS
  - least expensive and most common
  - not practical for some large structures
  - long lead wires increase signal “noise”

- **Method - Wireless transmission**
  - More expensive
  - Signals are transferred more slowly and are less secure
  - Use is expected to increase in the future

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(d) Data Sampling and Collection

General Rule:

- The amount of data should not be so scanty as to jeopardize its usefulness, nor should it be so voluminous as to overwhelm interpretation

Issues:

- Number of sensors and data sampling rates
- Data sorting for onsite storage
- In some cases, large volumes of data

Result:

- Efficient strategies needed for data sampling and storing

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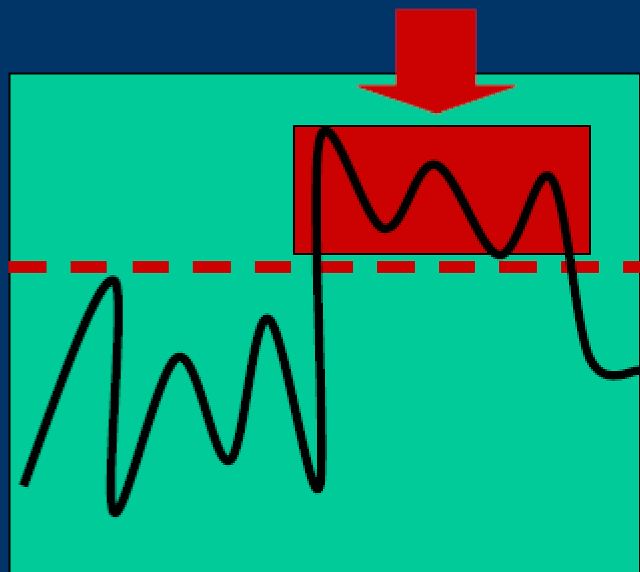
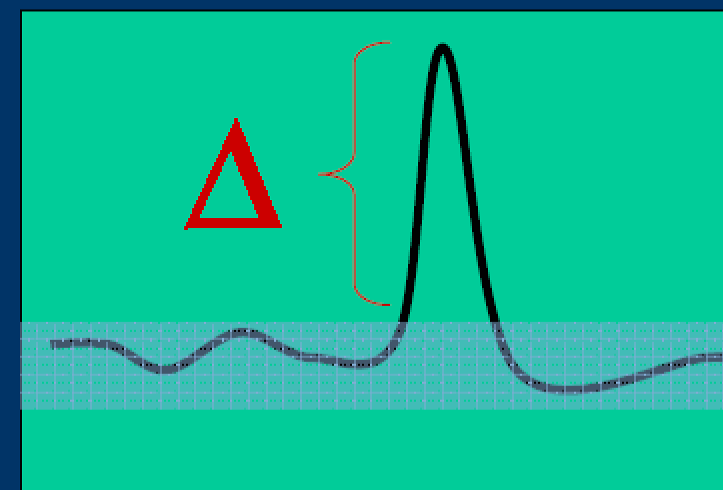
Example Data Acquisition Algorithms



Record only values greater than a threshold value

(and times that readings occur)



Record only significant changes in readings

(and times that changes occur)

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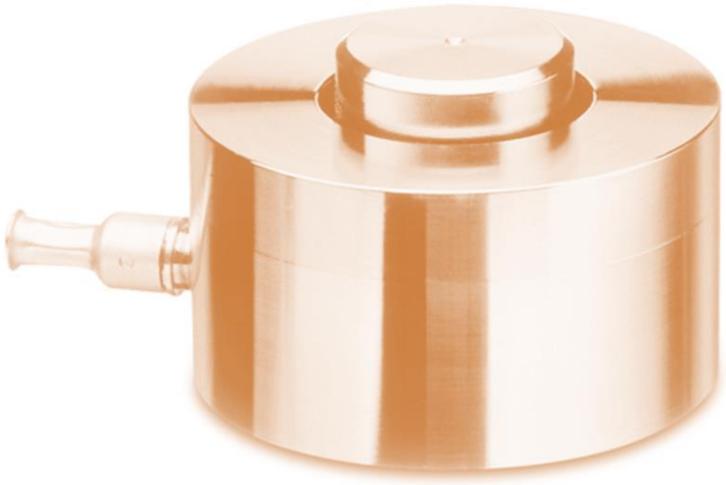
What is monitored, how and why?

Load

→ Magnitude and configuration of forces applied to a structure

- Are they as expected?
- How are they distributed?

→ Measured using load cells or inferred using strain data



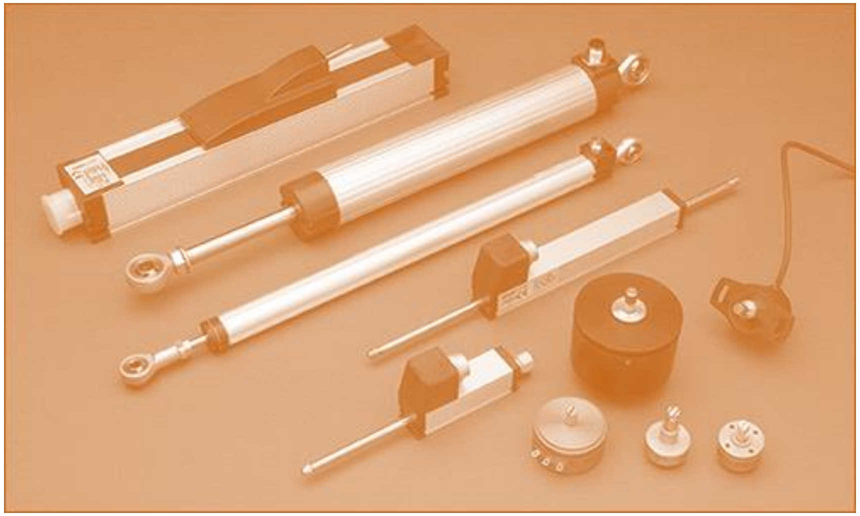
What is monitored, how and why?

Deformation

→ Excessive or unexpected deformation, may result in a need for rehabilitation or upgrade

- Are they as expected?

→ Measured using various transducers



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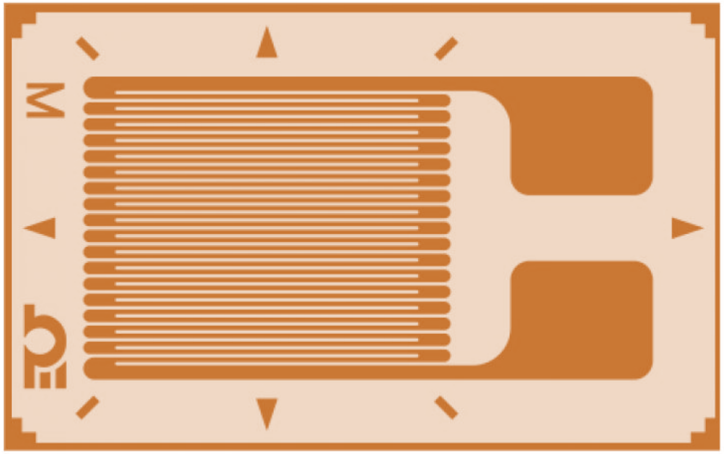
What is monitored, how and why?

Strain

→ Intensity of deformation

→ Magnitude and variation of strains can be examined to evaluate safety and integrity

→ Measured using strain gauges
- FOS, electrical, vibrating wire, etc.



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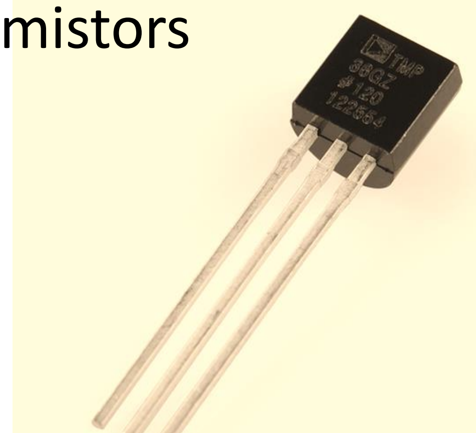
What is monitored, how and why?

Temperature

→ Changes in temperature cause deformation
- Thermal Expansion
- Repeated cycles can cause damage

→ Temperature affects strain readings
- Temp must be “removed” from strain data

→Measured using Thermocouples (TC), Temperature Indicator Controllers (TIC), thermistors



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What is monitored, how and why?

Acceleration

→ Loads cause accelerations of structural components and vice versa

- How is the structure resisting accelerations and the resulting loads?

→ Widespread use in highly seismic regions

→ Measured using accelerometers

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What is monitored, how and why?

Wind Speed and Pressure

→ Wind loads can govern the design of longspan bridges and tall buildings

- Record speed and pressure at various locations

→Measured using anemometers

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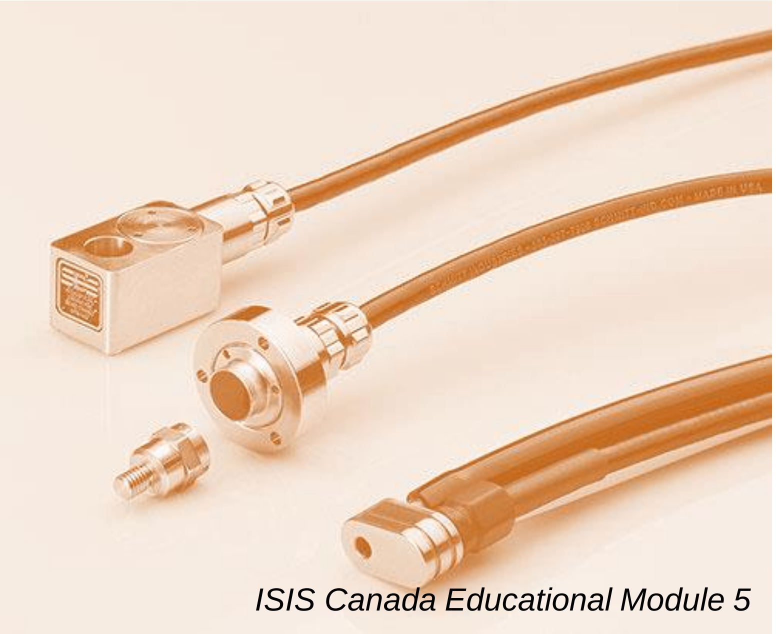
What is monitored, how and why?

Acoustic Emissions

→ When certain structural elements break, they emit noise
  - AE listens for the noises, and pinpoints locations using triangulation

→ Used in post-tensioned concrete and cablestayed structures

→ Measured using microphones



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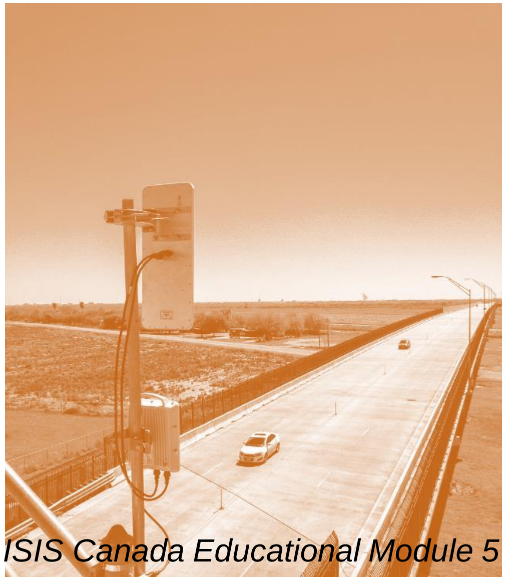
What is monitored, how and why?

Video Monitoring

→ Time-stamped videos and pictures can be used to witness extreme loads or events

- Data can be correlated with images
- Permits finding of overloaded trucks

→ Emerging internet camera technology is used



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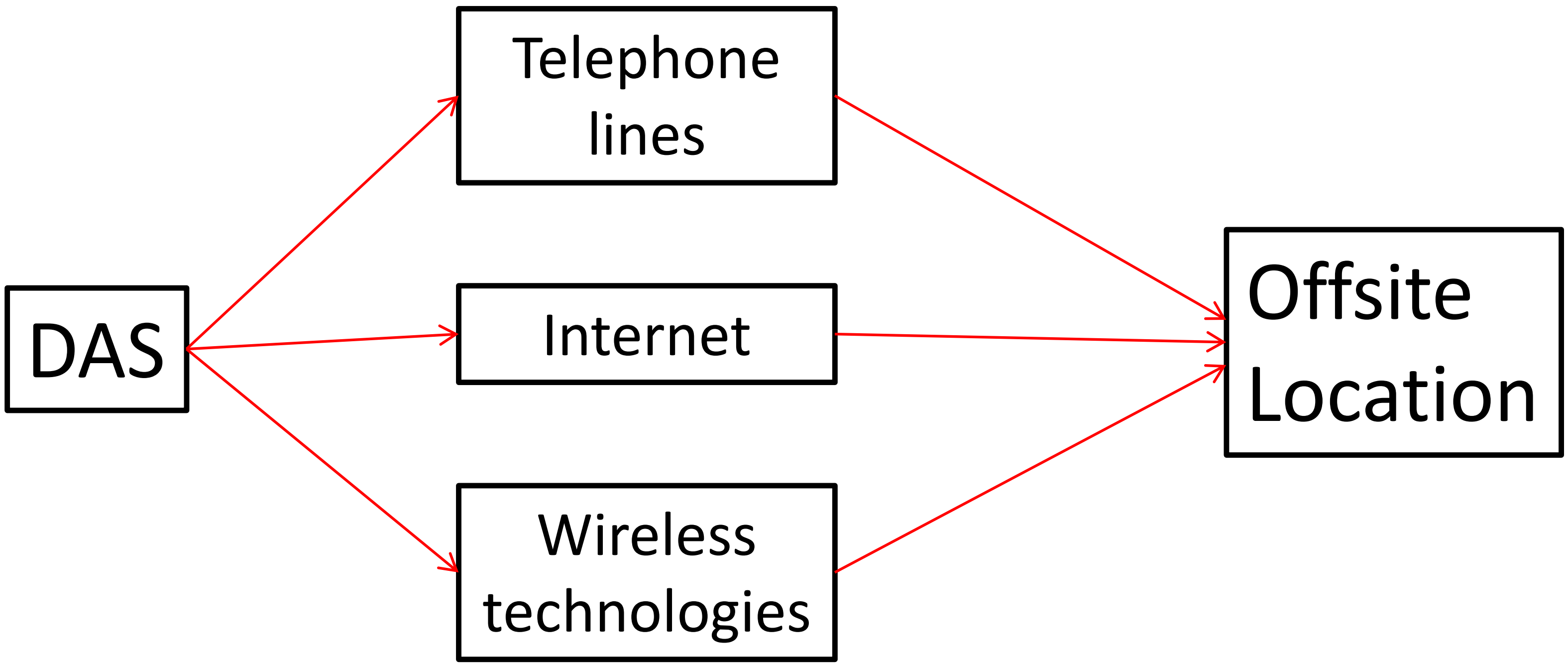
- Refers to data transfer from the DAS to an offsite location
- Allows for remote monitoring, elimination of site visits



• Required before data can be stored for later interpretation and analysis

• The goal is to remove mundane data, noise, thermal, or other unwanted effects and to make data interpretation:

- Easier
- Faster
- More accurate

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- Data may be stored for very long periods of time
  - Retrieved data must be understandable
  - Data must not be corrupted
  - Sufficient memory must be available

- Data files must be well documented for future interpretation

- It is common to disregard raw data and store only processed or analyzed data
  - This does not allow for re-interpretation

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- Extremely important component
  - Converts abstract data signals into useful information about structural response and condition

- No “standard” rules exist for diagnostics

- Methodology used depends on
  - Type of structure
  - Type and location of sensors used
  - Motivation for monitoring
  - Structural responses under consideration

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- When storing data for retrieval, consider
  1. Significance of data
  2. Confidence in analysis

Remember:
*The goal of SHM is to provide detailed physical data which can be used to enable rational, **knowledge-based engineering decisions**.*

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SENSOR TECHNOLOGY

- Many sensor types are currently available
  - Choice for SHM depends on various factors

- Fibre optic sensors (FOSs)
  - Newer class of sensors
  - Emerging for infrastructure applications

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FOS Advantages:

Stability → Increased long-term stability and decreased noise

Non-conductive → Immune to electromagnetic and radio frequency interference

Flexibility → Multiplexing and Distributed sensing

Convenience → Light, small diameters, noncorrosive, embeddable, easily bondable

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Sensing using optical fibres and techniques

- Light beam (laser) is sent down an optical fibre toward a gauged length
- Light waves measure changes in state (i.e. elongation or contraction)
- Change in reflected light waves is correlated to strain reading
- Demodulation unit calculates strain from light signals and gives voltage
- DAS converts voltage to strain data for processing

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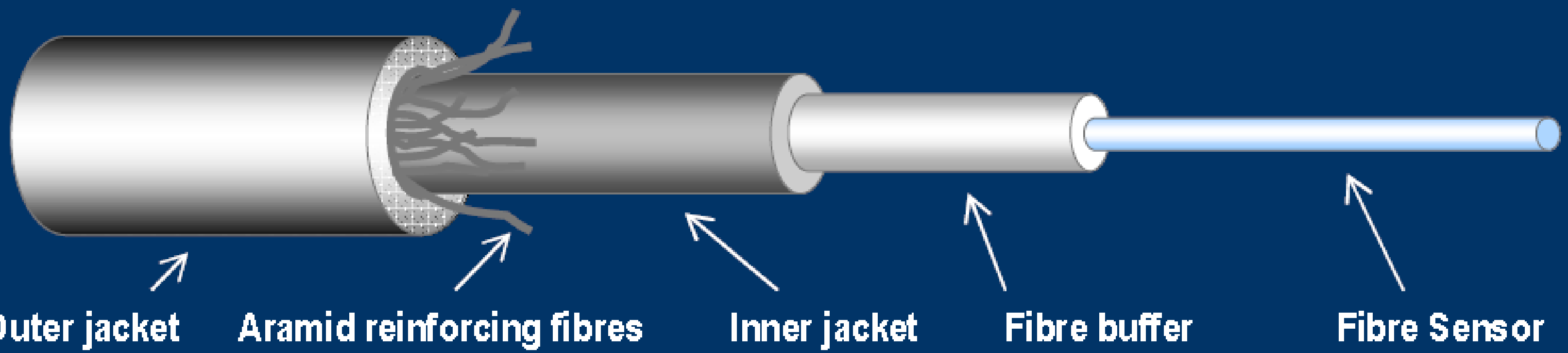
Typical Optical Fibre



Assorted fibre coatings are required to protect the fibre from…

Abrasion

Protection during handling and installation

Concrete

Alkaline environment is harmful to glass fibres

Moisture

Weakens the fibres and controls growth of microcracks

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Characteristics:

- Use for static and dynamic monitoring
- Embeddable, bondable and weldable
- Gauge length can vary from cm to more than 1 km
- Thermal and mechanical strains can be separated

Useful to measure:

  - Width of cracks
  - Strain transfer in bonded joints
  - Stress concentrations

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1. Design Issues

→ Definition of SHM objectives

↓

Types of monitoring

↓

Sensor placement

↓

Durability and lifespan of SHM

2. Installation Issues

Contractor education

↓

Sensor identification

↓

Sensor damage during construction

↓

Structural changes induced by presence of SHM system

↓

Protection against deterioration and vandalism

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3. Use Issues

Dissemination of performance results

Continuity of knowledge

Data collection and management

Public awareness

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1. Identify the damage or deterioration mechanisms

2. Categorize influence of deterioration on the mechanical response
   - Theoretical and numerical models of structure

3. Establish characteristic response of key parameters
   - Establish sensitivity of each to an appropriate level of deterioration

4. Select the parameters and define performance index
   - Relates changes in response to level of deterioration

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5. Design system
   - Selection of sensors, data acquisition and management
   - Data interpretation

6. Install and calibrate SHM system (baseline readings)

7. Assess field data and adapt system as necessary

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THE FUTURE OF SHM

- **SHM** is increasingly seen as an important tool in the **maintenance** of sustainable infrastructure systems

Ongoing advancements are expected, emerging technologies include:

→**Smart Composites**
→**Live Structures**

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Smart Composites

→ Composites (e.g. FRP) with sensors embedded inside that provide information about the condition of the structural component

Muscle/Member Analogy:

Muscles have nerve cells embedded in them that provide information to the brain about the conditions of the muscles ⟺ Smart composites have sensors inside that provide information about the structural members' condition

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Live Structures

- Represent the cutting edge of civil engineering design and analysis

- Live structures are capable of:
  - Sensing loads, deformations, and damage
  - Correcting and countering the load effects

- Presently structures are largely theoretical

- Accomplished using emerging self-actuating materials

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Structural Health Monitoring

→Provides the civil engineering community with a suite of **options for monitoring**, **analysing** and **understanding** the health of our infrastructure systems

→Provide **essential tools** to engineers who must take steps **to improve** the sustainability of infrastructure systems

SUMMARY AND CONCLUSION

Case Study – The Örnsköldsviks bridge - 2006

Assessment procedure for the bridge

Step 1

Initial assessment

- Site visits - several
- Study of documents
- Study and carried out simple calculations

Step 2

Intermediate assessment

- Further inspections
- Material testing, cores etc
- Detailed calculations
- Investigations of loading etc
- Planning for testing etc
- Simple FE-Models.

Step 3

Enhanced assessment

- Laboratory investigations
- Investigations of Load Models
- Reliability based investigations
- Strengthening calculations
- Monitoring
- Refined calculations, FE-models
- Decision analysis

Step 4

Destructive testing

- Design Models
- Ultimate Limit State
- Verification
- Detailed analysis
- Non-linear FE-Models

Björn Täljsten

Case Study – The Örnsköldsviks bridge - 2006

Structural Assessment

S1: Survey

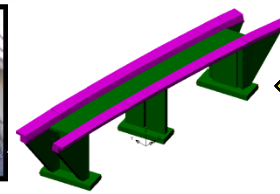
Bridge owner/Consultant

S1: Questionnaire

Bridge owner/consultant

S2: Condition assessment

Visual Inspections

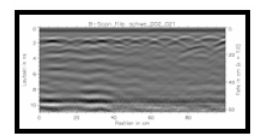


S2: Simple FE

Consultant

S2: Non destructive tests

Radar, ultrasonic tests etc.



S2: Material samples

Drilling of cores, pull-off etc.

S3: Laboratory testing

Concrete, Steel etc.

Björn Täljsten

Case Study – The Örnsköldsviks bridge - 2006

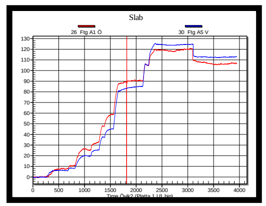
Structural Assessment

S3: Sensor installation

Specialist consultant


S4: Load test 1

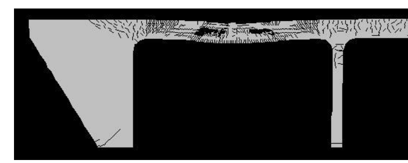
Testing institutes

S4: Strengthening

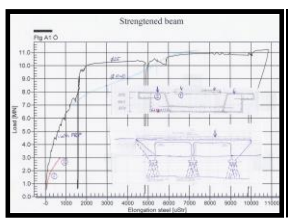
Specialist contractors



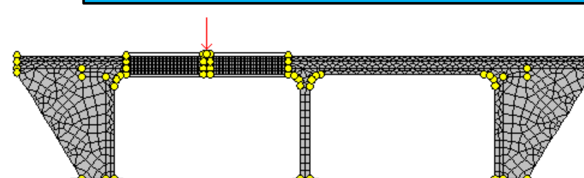


S4: Load test 2

Testing institutes



S4: Detailed evaluation



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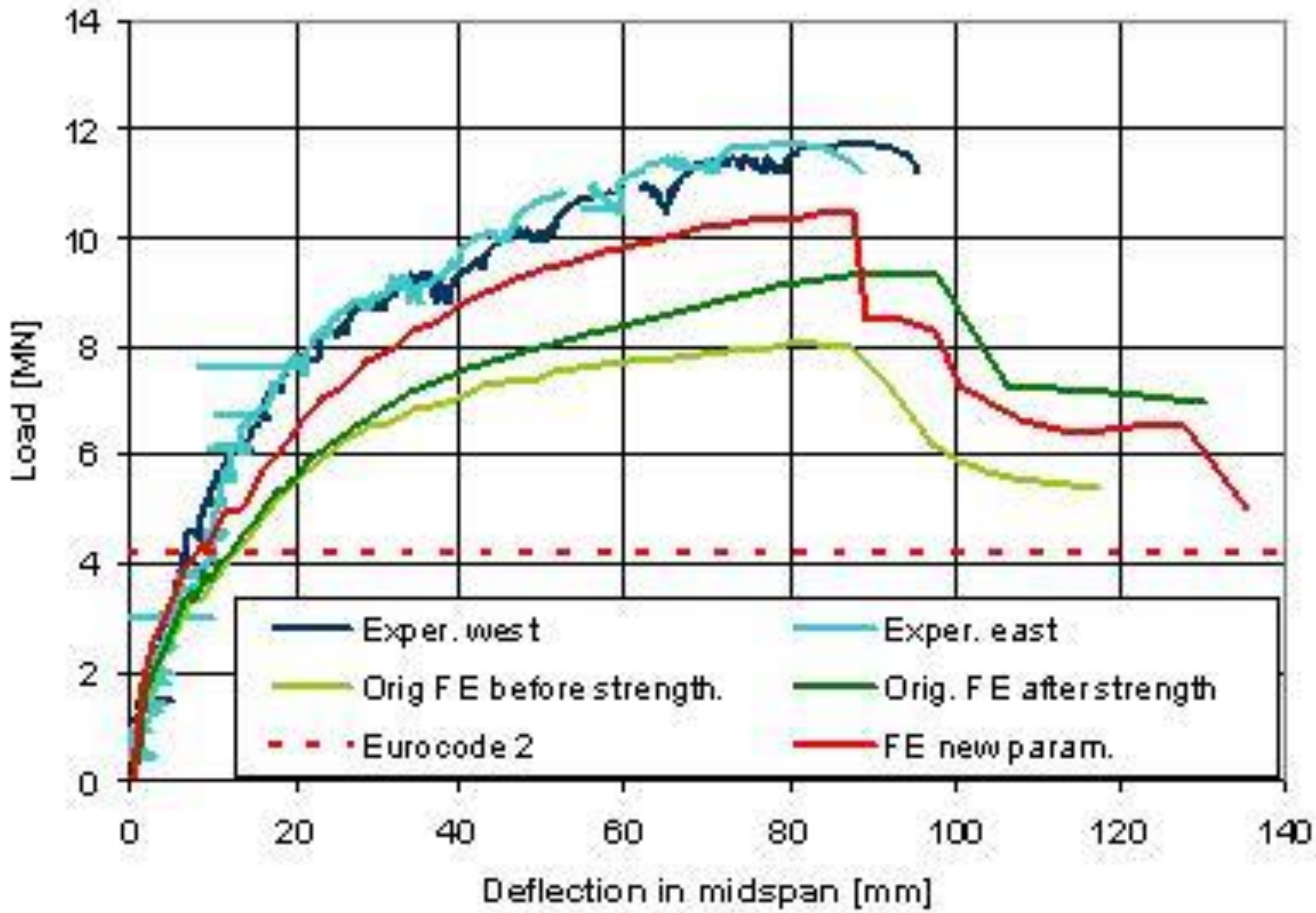
Case Study – The Örnsköldsviks bridge - 2006

Predicted Load-Carrying Capacity



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SUMMARY AND CONCLUSION

Case Study – The Örnsköldsviks bridge - 2006

Predicted Load-Carrying Capacity

• Eurocode 2, $\theta = 30^o$	P = 6,1 MN
• Eurocode 2, $\theta = 22^o$	P = 8,8 MN
• MCFT, Response, $\theta \approx 30^o$	P = 8,7 MN
• 2D Non-linear, Atena, $\theta \approx 30^o$	P = 10,8 MN
• Test, $\theta \approx 30^o$	P = 11,7 MN

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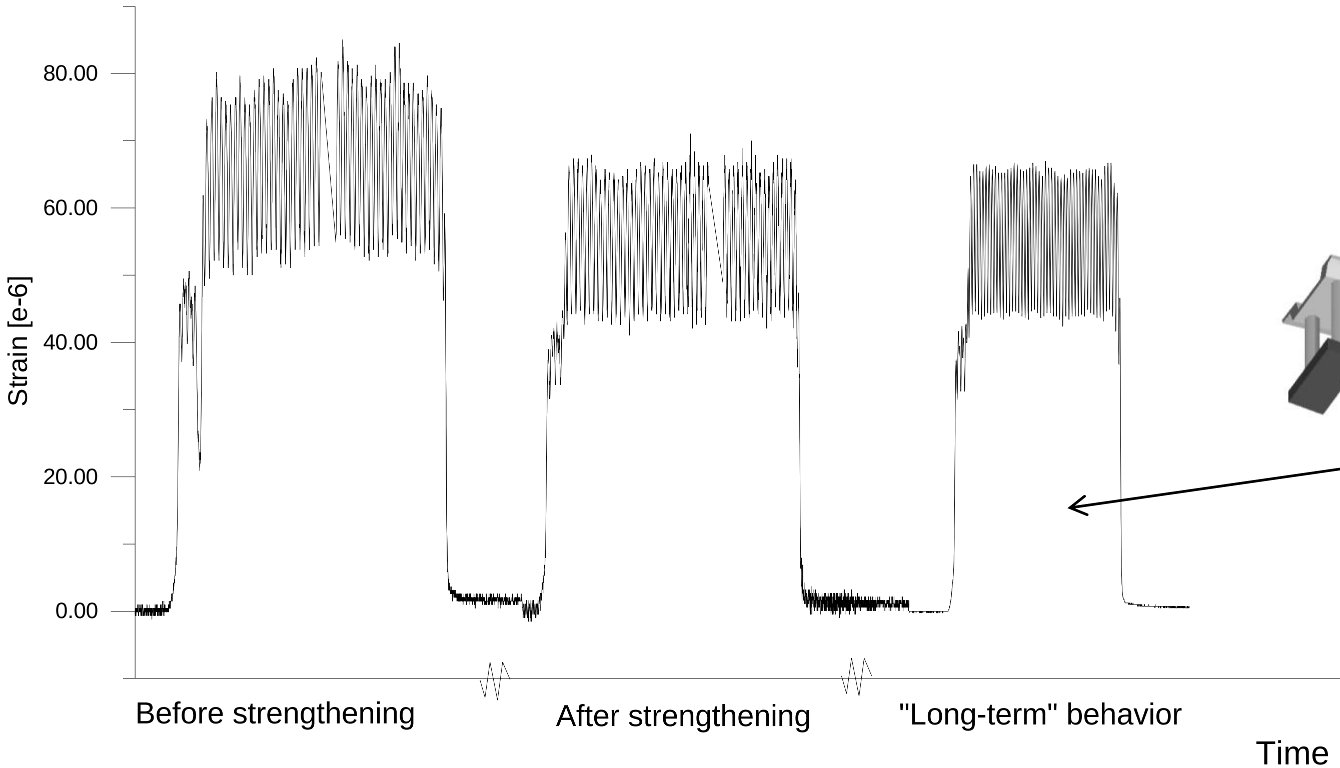
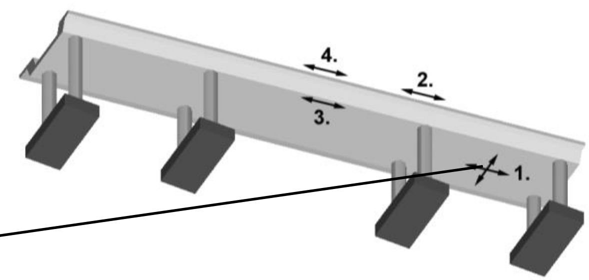
SUMMARY AND CONCLUSION

Case Study – Kallkällan - 1998

Periodic long-time monitoring



Strains



Measurement of strains

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