



A REVIEW

DAMAGE DETECTION AND CONDITION ASSESSMENT OF CIVIL ENGINEERING STRUCTURES USING STRUCTURAL HEALTH MONITORING

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REVIEW ARTICLE OBJECTIVES

- To provide a **general awareness of Structural Health Monitoring (SHM)** and its potential applications of Damage assessment.
- To define the **motivation for SHM Technology Development** and the **anticipated Benefits and Outcomes** of SHM.
- **To highlight:**
 - **Limitations of traditional damage detection** strategies for the critical and historical structures.
 - **Merits and disadvantages** of different approaches for SHM and damage identification.
 - **Critical issues for future research** on SHM and damage identification.

OUTLINE OF THE REVIEW

- **Traditional Damage Detection Strategies**
- **Introduction to Structural Health Monitoring (SHM)**
 - State of Problem and Motivation for SHM Technology Implementation
 - SHM Objectives
 - Requirements for SHM implementation
- **Steps for Successful Implementation of SHM**
 - Instrumentation and Measurement
 - SHM Testing Categories
 - Data Analysis Methods for Damage Assessment
 - Global vs. Local Damage Detection
 - Technological Barriers & Solutions
 - Structural Monitoring Challenges
 - Future Trend
 - Benefits and Outcomes of SHM

TRADITIONAL DAMAGE DETECTION STRATEGIES

- Civil engineering infrastructures deteriorate with time (fatigue failure, effects of environmental conditions, extreme events such as an earthquake/floods)
- The traditional damage detection strategies (visual inspection, localized non-destructive evaluation such as **radio X-ray, radiographic, eddy current and ultrasonic techniques**).
- foreseen damage location, vicinity of the damage is known a priori, accessible, in-depth damages or inaccessible components).
- large and complex structures, visual inspection is inefficient and expensive, subjective.
- To address these issues, **Global damage detection techniques** that use vibration-based nondestructive testing such as **Structural health Monitoring SHM** should considered.

STRUCTURAL HEALTH MONITORING (SHM)

- Assess the in-service performance of structures: Through **Implementation of a damage detection strategy for sensing of the structural response in conjunction with data aggregation and model updating to evaluate the structure condition.**

Damage Identification Process using SHM

- **Detection** “Is there damage”
- **Localization** “where is the damage”
- **Type** “What kind of damage”
- **Quantification** “How severe”
- **Prognosis** “Future prediction”



SHM APPLICATIONS

- Buildings (critical or even historical)
- Bridges
- Tunnels
- Offshore
- Wind Generators



>> Practically: any critical structure

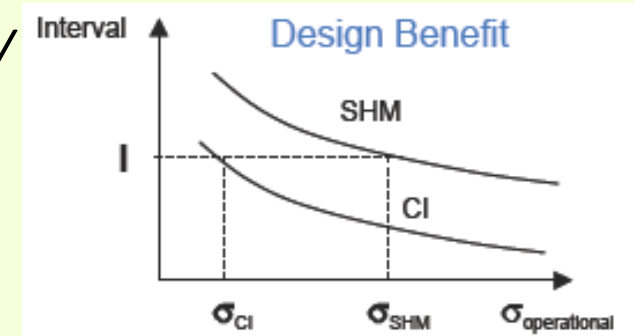
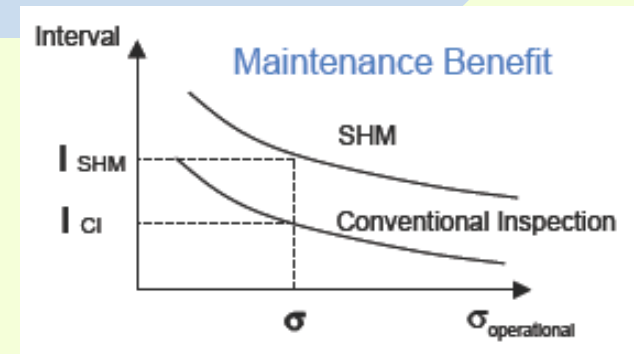
STATEMENT OF THE PROBLEM

- The traditional damage detection method for complex structures is inefficient and expensive, subjective.
- *Extensive degradation due to unsatisfactory inspection* ⇒ **Repair costs become comparable to replacement costs**
- *Corrosion of conventional steel reinforcement within concrete* ⇒ **Reductions in strength and serviceability “repair and/or replacement”**
- *Increased loads or design requirements over time* ⇒ **Structures deemed unsafe or unserviceable “strengthening or replacement”**
- *Deterioration and/or ageing* ⇒ **“Repair or strengthening or rehabilitation”**
- *Catastrophic events (earthquake, hurricane, explosion...etc.)* ⇒ **post-hazard damage assessment for decision making**
- *Continuous vibrations /cyclic stress* ⇒ **fatigue assessment**

SHM IMPLEMENTATION MOTIVATION

- **SHM Implementation is motivated by:**

- *The potential life-safety and economic impact*
- *better management of existing structures*
- *Appropriate repair, rehabilitate and/or strengthening of structures*
- *Monitor and ensure the safety of as yet unproven materials and systems*
- **“Innovative designs / new materials”**
- *Minimize the uncertainty associated with post-earthquake damage assessments, hence prompt reoccupation of buildings*
- *Advances in sensors, data Acquisition/transmission/processing and Wireless and internet technologies*



SHM OBJECTIVES

- Introduce Damage Assessment at different levels: **Detection**; identify if a damage has occurred or not. **Localization**; define its location. **Severity**; estimate its severity. **Prognosis**; evaluate the residual life of the structure.
- Provide warning of impending abnormal states or accidents to avoid casualties. Assessment of post-earthquake structural integrity.
- Inform maintenance and rehabilitation decisions based on structure performance/condition, reduce maintenance costs
- Increase reliability, improve safety and enable light weight design
- Feedback loop to improve future design based on experience
- Evolve into potentially more cost effective condition-based maintenance philosophies.

REQUIREMENT FOR SHM IMPLEMENTATION

SHM is a very multidisciplinary field

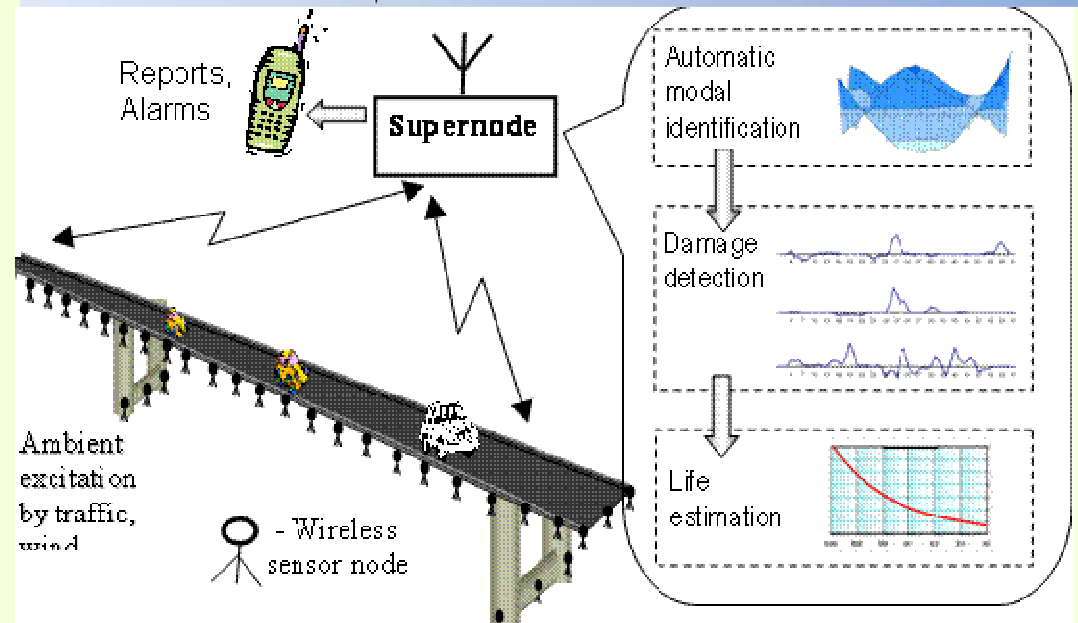
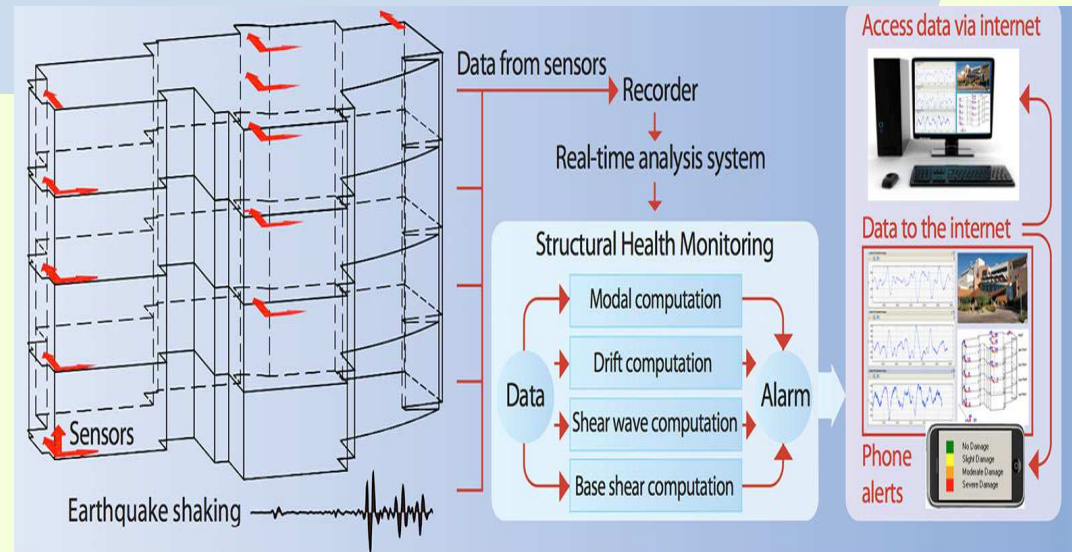
- Seismology,
- Electronic and
- Civil engineering,
- Computer science

SHM involves

- Sensing technology,
- Power technology,
- Communication technology,
- Storage technology,
- Signal processing, and
- Health evaluation algorithm.

STEPS FOR SUCCESSFUL IMPLEMENTATION OF SHM SYSTEM

- Instrumentation: Sensor networks (sensor type, number, layout),
- Excitation mechanism (Forced or ambient excitation)
- data measurement and data acquisition, data transmit.
- Signal processing, data reduction and structural feature extraction, for **modal parameters identification**
- Statistical analysis, Condition assessment and Damage detection algorithm



INSTRUMENTATION AND MEASUREMENTS

Measure:

- Acceleration
- Strain
- Climatic Conditions
- Curvature
- Displacements
- Load/force/torque
- Tilt/Slope
- Twisting/Rotation/
- Distortion

Sensors:

- Strain Gauges
- Piezoelectric Transducers
- Laser Doppler Vibrometer (LDV)

Smart Sensors

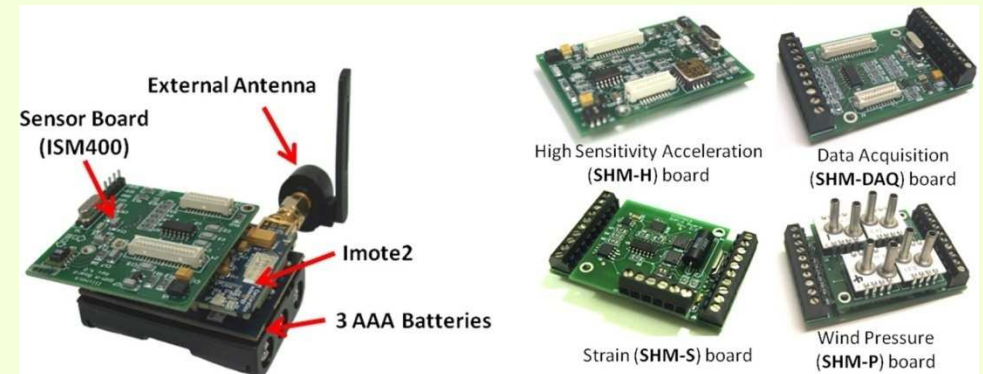
- Fibre Optic Sensors (FOSs)
- Magnetostrictive Sensors

Active Sensors

- Piezoelectric Sensors
- Self-Diagnosing Fibre reinforced Composites

Identify

- Corrosion
- Cracking
- Strength
- Tension
- Location of rebar/delaminations



ATTRIBUTES OF SENSORS

The design of sensing systems depends on the choice of sensors whose attributes match the requirements of the application

- **Accessibility:** Capability of sensors associated with specific precision in certain range.
- **Operating Range:** Designed range of sensors for optimal performance.
- **Data Format:** Measuring feature of data in time; continuous or discrete/analog or digital.
- **Sensitivity:** Minimum magnitude or change in the environment sensors can detect.
- **Intelligence:** Capabilities of on-board data processing and decision-making.
- **Active versus Passive Sensors:** Capability of generating vs. just receiving signals.
- **Physical Contact:** The way sensors observe the disturbance in environment.
- **Operating Principle:** Embedded technologies that make sensors function, such as electro-optics, electromagnetic, piezoelectricity, active and passive ultraviolet
- **Accuracy:** a measure of the closeness of the sensor actual output to the ideal output.

OPTIMUM CRITERIA FOR SENSOR PLACEMENT

Effective Independence Method - EIM

The EIM deals with the goal to maximize both spatial independence and signal strength of the target mode shapes by maximizing the determinant of the associated Fisher information matrix.

Driving point residue (DPR) method

The modal participation factor or DPR is a mechanic optimum criterion.

Kinetic energy-based method

In KEM, the objective is to maximize the measure of the kinetic energy of the structure.

Eigenvalue vector product (EVP) method

The EVP is a mechanic-type criterion. This criterion forms an indicator consisting in the absolute value of the product of every eigenvector.

Non-optimal driving point (NODP) method

The NODP method is based on the well-known concept that the amount of vibration energy of any mode shape depends on the relative positions of the excitation sources.

FIELD TESTING

Static Field Testing:

Behavior tests: verify the methods of analysis

Diagnostic tests: locate the sources of distress that might exist

Proof tests: study the load-carrying capacity

Periodic Monitoring:

Through ambient vibration: to examine the dynamic response of the structure and identify changes in the vibration characteristics which might signal damage.

Through testing under moving traffic or static field testing: track changes in the behavior of a structure and validate the design.

Dynamic Field Testing:

Stress history tests: determine the range of stresses experienced by fatigue loading

Ambient vibration tests: identify the vibration characteristics of a bridge by measuring its response to ambient dynamic forces

DLA tests: Dynamic Amplification Factor due to moving truck passing over bridge

Pullback tests: response to lateral dynamic excitation

Continuous Monitoring:

Active monitoring

Passive monitoring

FULL SCALE DYNAMIC TESTS

Forced vibration excitations:

- Forced excitation (vibration induced by impact hammer, Bumper, eccentric mass shaker)
- Expensive, time consuming to conduct and often require special permissions.
- Pre-meditated and precise.
- Much higher signal-to-noise ratio.
- Amenable to extremely low duty cycle functioning.
- Effective in obtaining accurate estimation of higher modes



Eccentric Mass Exciter

Damage Detection and Condition Assessment of CE Structures Using SHM

Ambient vibration excitations:

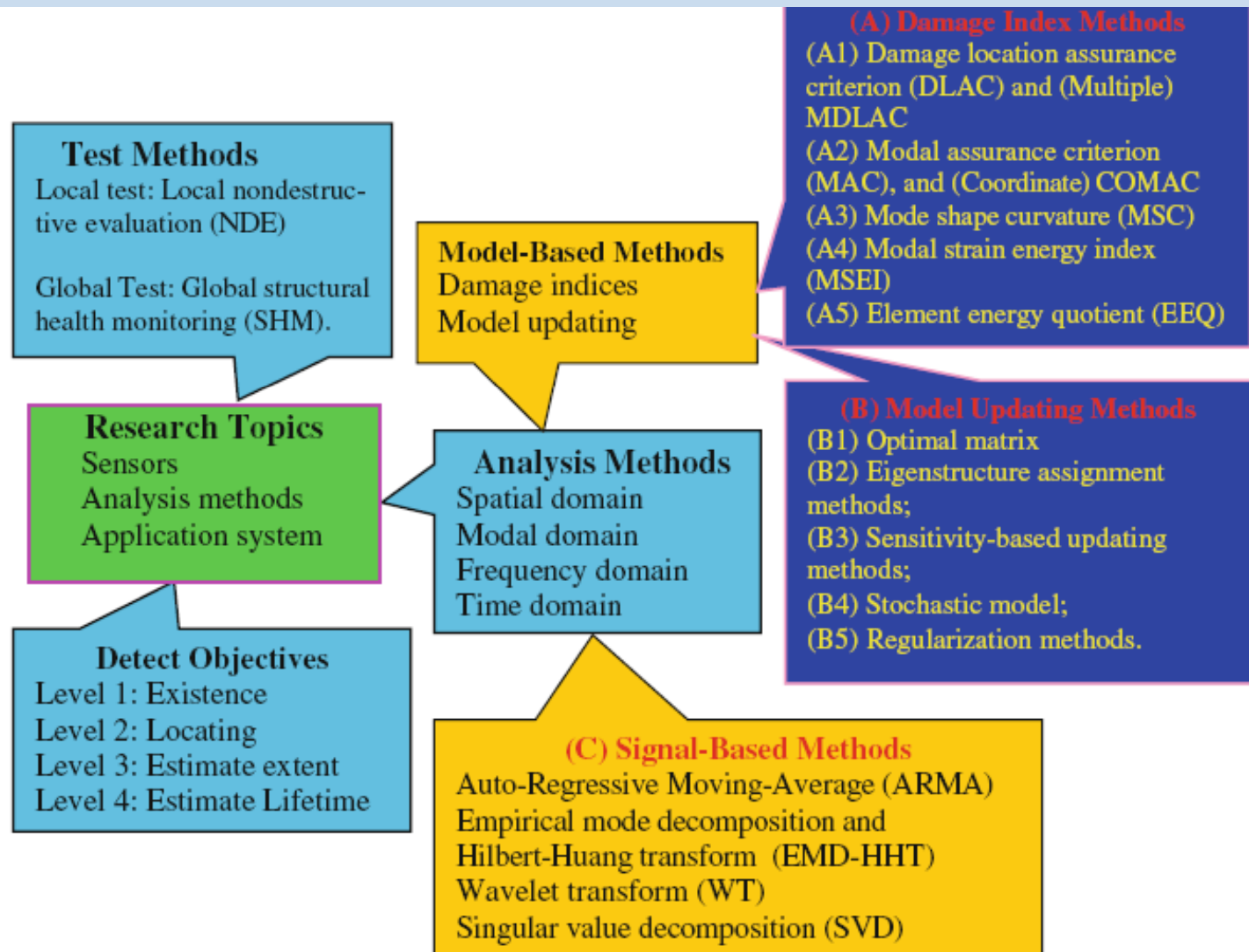
- *ambient excitation* (vibration induced by wind, passing traffic, operation use, earthquake)
- Economical, non-destructive, fast and easy to conduct.
- Unpredictable in nature and timing
- *Low signal-to-noise ratio.*
- *Require continuous monitoring; hard to implement duty cycles.*



Operational Use of Building

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DATA ANALYSIS METHODS FOR CONDITION ASSESSMENT



LOCAL AND GLOBAL TECHNIQUES

Local

- **Local inspection techniques** focus on detecting highly localized, imperceptible fractures in a structure
- Require a significant amount of time
- Disrupt the normal operation of the structure
- Detect *tiny cracks* (mm/cm) and small corroded patches.
- Use *sophisticated imaging techniques* – 250KHz ultrasound, x-ray, thermal, magnetic etc.
- *Can detect damages within a few inches of the equipment*

Global

- **Global inspection techniques** aim to detect a damage or defect that is large enough to affect the entire structure
- researcher have been developing and testing *wireless sensor networks as global inspection techniques*
- Target larger damages e.g. undermined cables, braces or columns
- Use accelerometers to collect structural response.
- Detect structural damages in the entire structure

MODEL BASED METHOD V.S. MODEL-FREE METHOD

Model based methods:

- Measure changes of modal parameters (natural frequency, mode shape, damping, etc.) and compare with numerical models using data analysis methods.
- Model-based diagnostic approach and frequency domain identification; natural frequency and mode shape identification; static bending moment comparison; flexibility/stiffness matrix model; modal strain energy.
- FE Modeling is needed, Low sensitivity to small damage, low accuracy in damage localization, on-site application (interference with environmental noise), relatively simple data Analysis

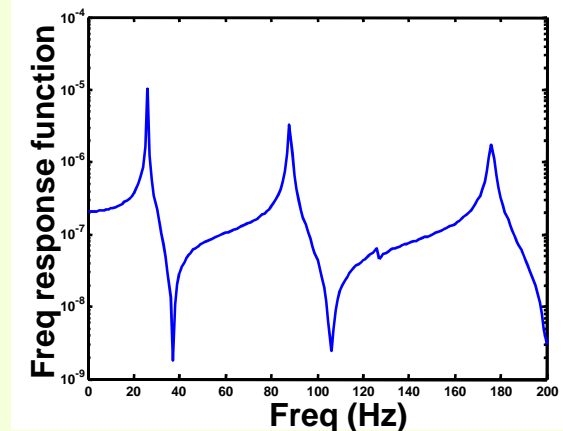
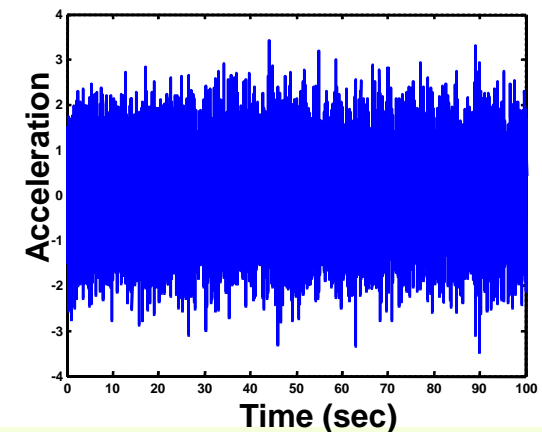
Model free methods:

- Statistical data analysis (pattern recognition) using sophisticated algorithms, without comparison with mathematical models
- Neural network method; Bayesian statistical system identification framework; Bayesian hierarchical model and artificial neural networks method; wavelets decomposition and wavelet coefficients analysis; Hilbert transform and Kalman filter; genetic algorithms
- no need for FE modeling, Low sensitivity to small damage, damage localization practically impossible, on-site application (interference with environmental noise), complex data analysis

VIBRATION-BASED SHM ALGORITHMS, IDENTIFICATION OF DATA FEATURES

SHM process is the identification of data features that allows one to distinguish between the undamaged and damaged structure.

- **Direct use of Modal parameters**
 - Natural frequency changes
 - Mode shapes
 - MAC, COMAC and Modal damping
 - Modal strain energy
 - Dynamic flexibility / stiffness matrix
 - Anti-resonances
- **Changes in Frequency Response function**
 - MAC for Frequency Response Function FRF
 - Frequency Response curvature
 - Coupling response measurement
- **Nonlinear Analysis**
 - Higher order FRF
 - Higher order frequencies and dynamic response
 - Harmonic Balance method



VIBRATION-BASED SHM ALGORITHM

Three objective functions are proposed:

- Frequency (Eigenvalue) changes

$$J = \sum_{i=1}^{nm} W_{\lambda_i}^2 \left(\left[\frac{\lambda_i(\{\alpha\}) - \lambda_i^0}{\lambda_i^0} \right]^A - \left[\frac{\lambda_i^D - \lambda_i^U}{\lambda_i^U} \right]^E \right)^2 \quad \left\{ \begin{array}{l} \text{Number of measured modes: } nm \\ \text{i-th eigenvalue: } \lambda_i \\ \text{Undamaged and damaged states: } U, D \end{array} \right.$$

- Mode shape changes:

$$J = \sum_{i=1}^{nm} W_{\phi_i}^2 \sum_{j=1}^{np} \left([\phi_{ij}(\{\alpha\}) - \phi_{ij}^0]^A - [\phi_{ij}^D - \phi_{ij}^U]^E \right)^2 \quad \left\{ \begin{array}{l} \text{Number of measured points: } np \\ \text{j-th component of the i-th mass normalized} \\ \text{mode shape: } \phi_{ij} \end{array} \right.$$

- Frequency changes combined with mode shape changes:

$$J = \sum_{i=1}^{nm} W_{\lambda_i}^2 \left(\left[\frac{\lambda_i(\{\alpha\}) - \lambda_i^0}{\lambda_i^0} \right]^A - \left[\frac{\lambda_i^D - \lambda_i^U}{\lambda_i^U} \right]^E \right)^2 + \sum_{i=1}^{nm} W_{\phi_i}^2 \sum_{j=1}^{np} \left([\phi_{ij}(\{\alpha\}) - \phi_{ij}^0]^A - [\phi_{ij}^D - \phi_{ij}^U]^E \right)^2$$

DAMAGE LOCATION ASSURANCE CRITERION (DLAC)

- DLAC approach identifies damage by evaluating the linear correlation between frequency change vectors obtained by experimental measurements and an analytical model.

$$\delta\omega_j = (\omega_{healthy}^a - \omega_j^a) / \omega_{healthy}^a$$

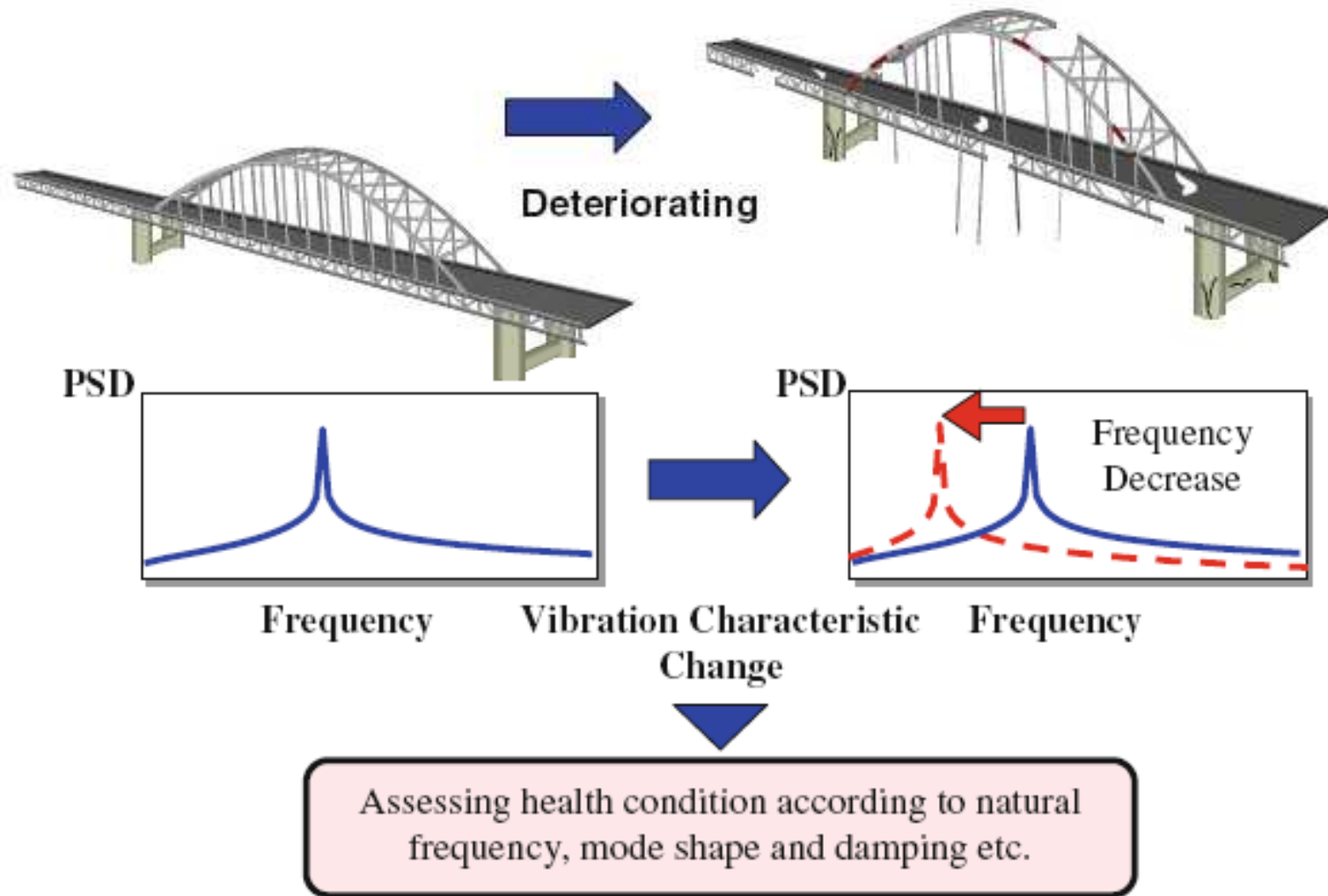
Analytical frequency change vectors

$$\Delta\omega = (\omega_{healthy} - \omega_{damage}) / \omega_{healthy}$$

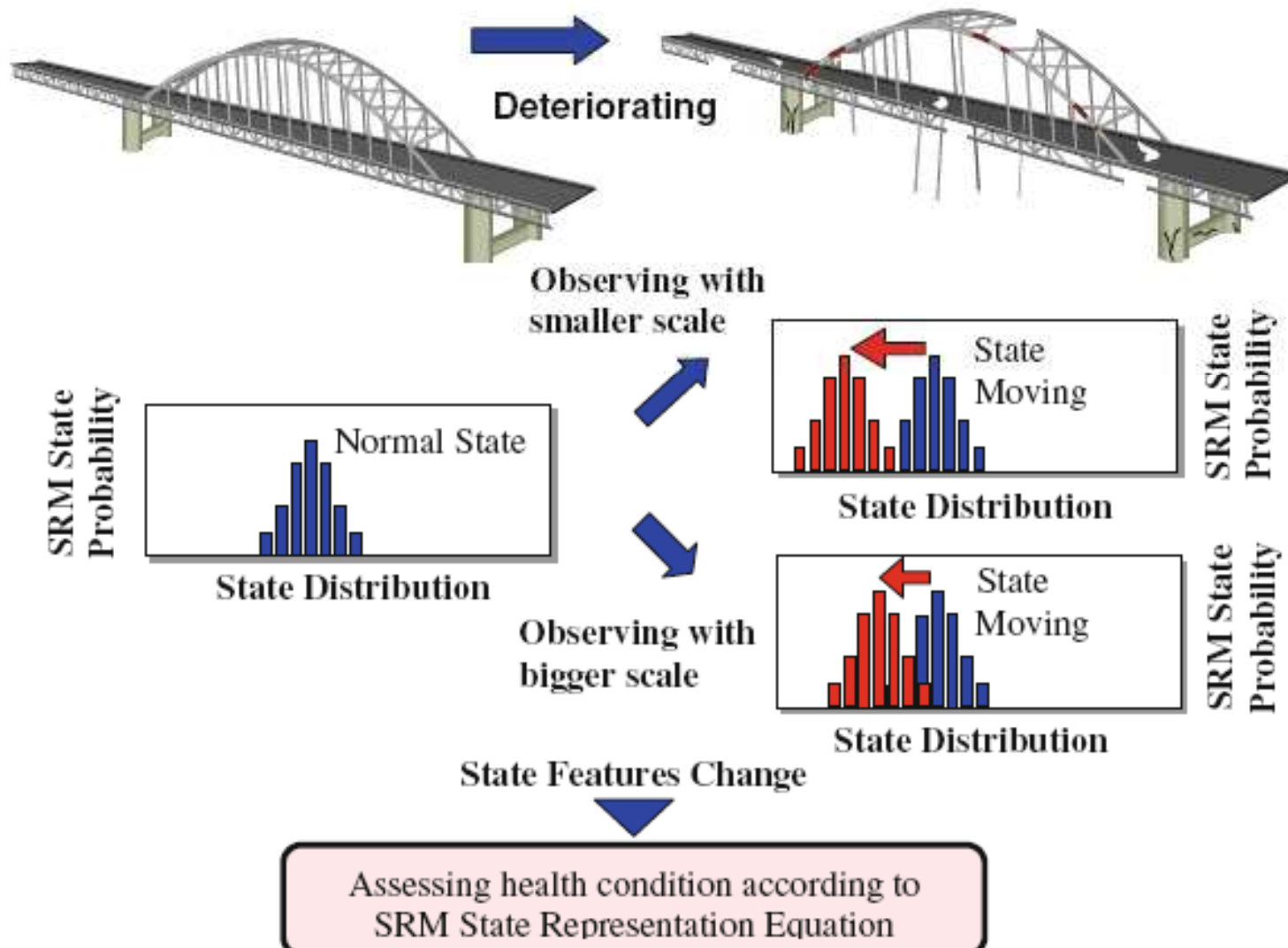
Experimental frequency change vectors

$$DLAC_j = \frac{|\{\Delta\omega\}^T \{\delta\omega_j\}|^2}{(\{\Delta\omega\}^T \{\Delta\omega\})(\{\delta\omega_j\}^T \{\delta\omega_j\})}$$

FREQUENCY DOMAIN DECOMPOSITION (FDD) PRINCIPLE



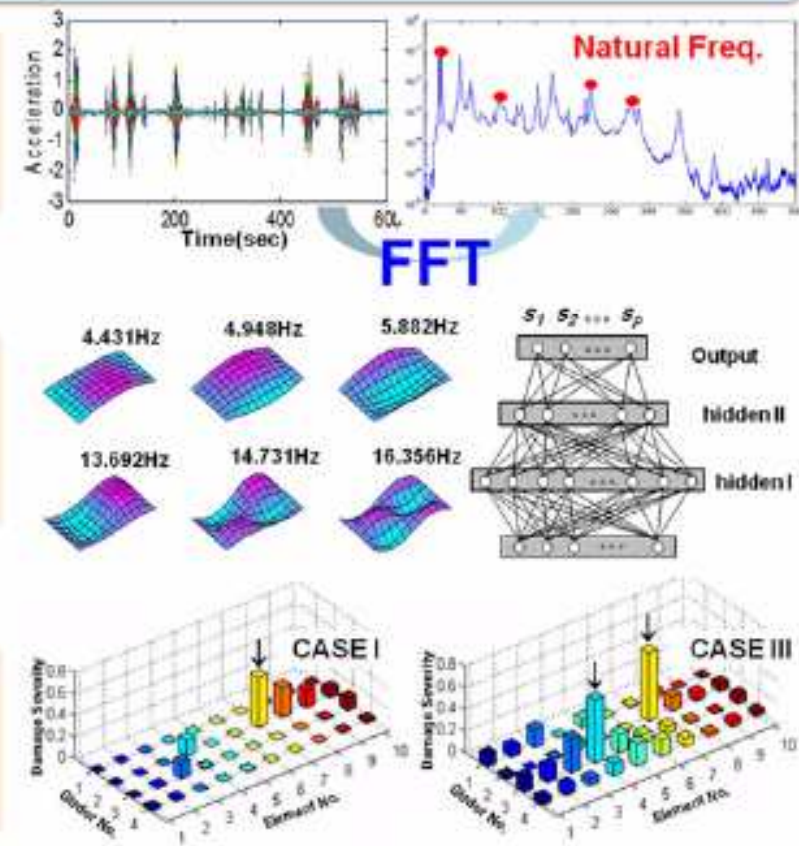
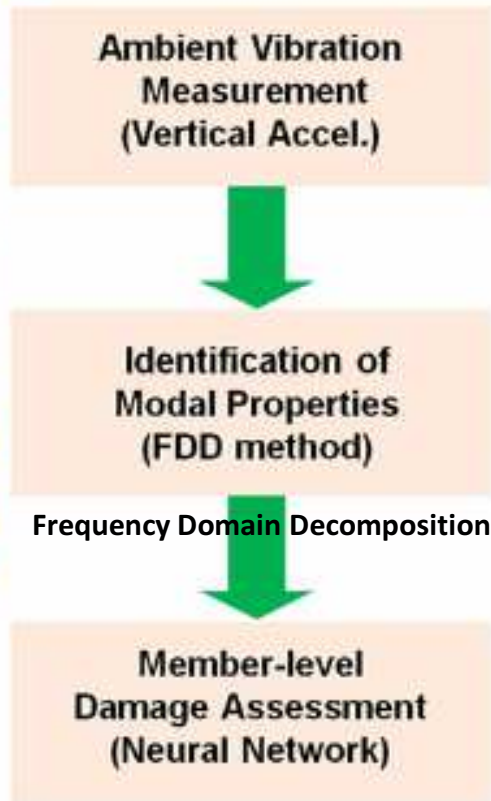
STATE REPRESENTATION METHODOLOGY (SRM) FOR CONDITION ASSESSMENT



NEURAL NETWORK (NN) FOR BRIDGE CONDITION ASSESSMENT



Analysis Procedure

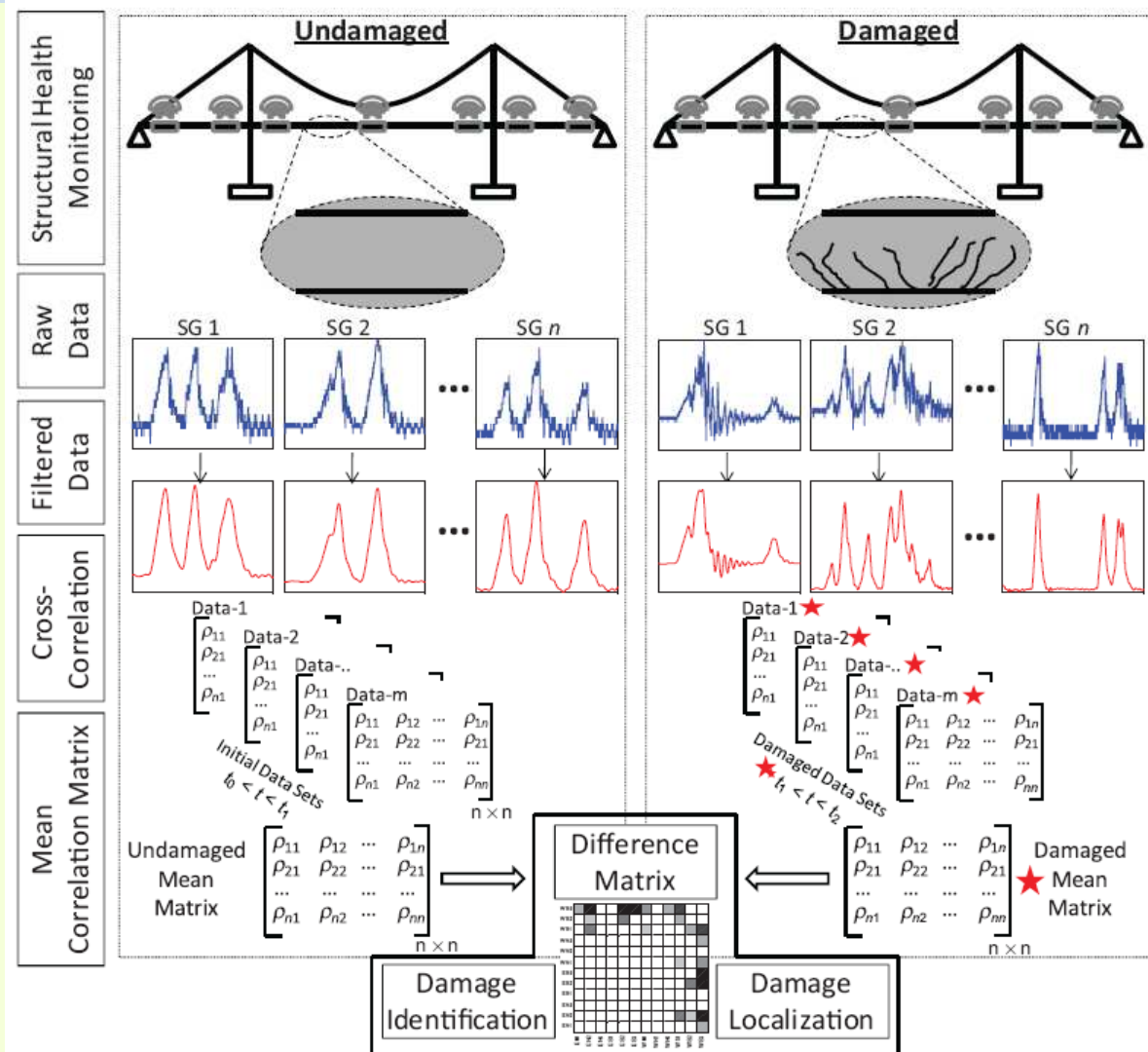


Large training sample is needed for accurate detection, Do not need knowing the physical relationships between the structural properties and damage occurrence

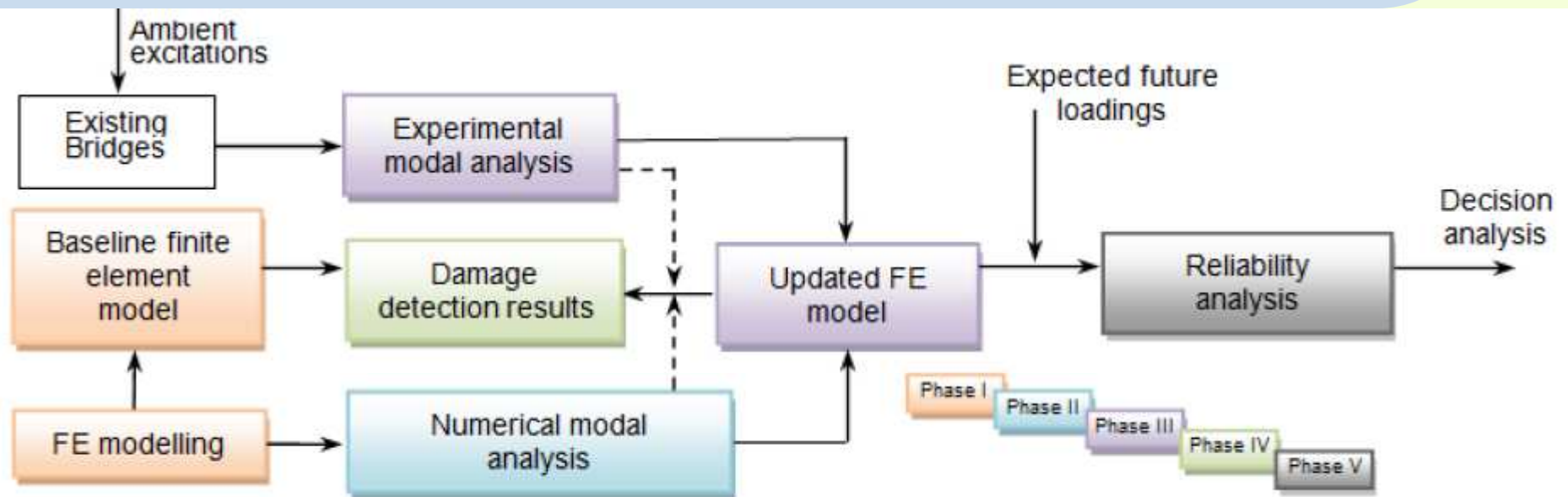
NON-PARAMETRIC DATA ANALYSIS APPROACH

Non-parametric data analysis approach is used for detecting and localizing structural changes using strain data under operational loading conditions.

The approach is based on tracking correlation coefficients between strain time histories at different locations.



PROCEDURE FOR DAMAGE DETECTION OF BASED ON VIBRATION MEASUREMENT



- A structure model is set up in the FE environment according to the as-built drawings.
- The baseline FE model can be established \Rightarrow the required dynamic/modal parameters.
- The experimental detection will update the numeric.
- From the updated FE model, the damage detection results and the safe condition of the structure will be summarized.
- The reliability or the remaining load-carrying capacity will be analyzed to help authorities to choose maintenance strategies.

MODEL UPDATING AND CONDITION ASSESSMENT

The model updating methods for damage detection shall be classified into four categories:

- 1)Optimal Matrix Updating Methods;
- 2)Eigenstructure Assignment Methods;
- 3)Sensitivity-Based Updating Methods;
- 4)Stochastic Model Updating Methods.

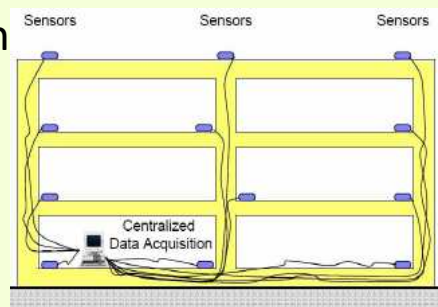
Critical steps in condition assessment related to damage diagnostics may be summarized as

- (1)setting up the parameters limits which categorizes the condition status;
- (2)diagnosing the damage existence;
- (3)localizing the damage;
- (4)defining the damage severity;
- (5)Assessing the effects of damage on structural reliability

BARRIERS & TECHNOLOGICAL SOLUTIONS

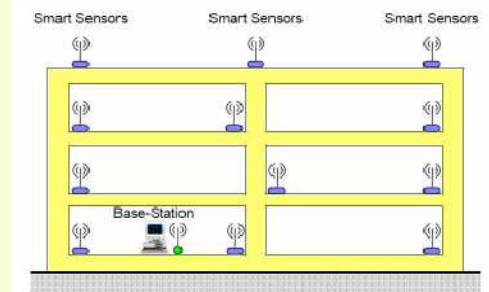
The Barriers up today

- Conventional cables
- High installation costs
- Vulnerable to ambient signal noise corruption
- Vulnerable to earthquake conditions
- Size and complexity of large structures require a large number of sensing points to be installed.
- Traditional SHM using Centralized data Acquisition



Technological Solutions

- Wireless Sensors
 - Accelerometers/Inclinometers
 - Laser Scanning
- Wireless Radio-frequency identification - RFID (Passive Sensor, Battery-Free)
- Acoustic Emissions
- MEMS (MicroElectroMechanical Systems)
- Increase of Computation capabilities
- Fiber technologies
- Smart sensors and base station



CHALLENGES IN VIBRATION-BASED SHM

Typical localized damage of interest in practical SHM applications may not induce significant influence on the dominant lower frequencies and the corresponding mode shapes of the monitored structure (unless it happens to occur at locations of high strain energy).

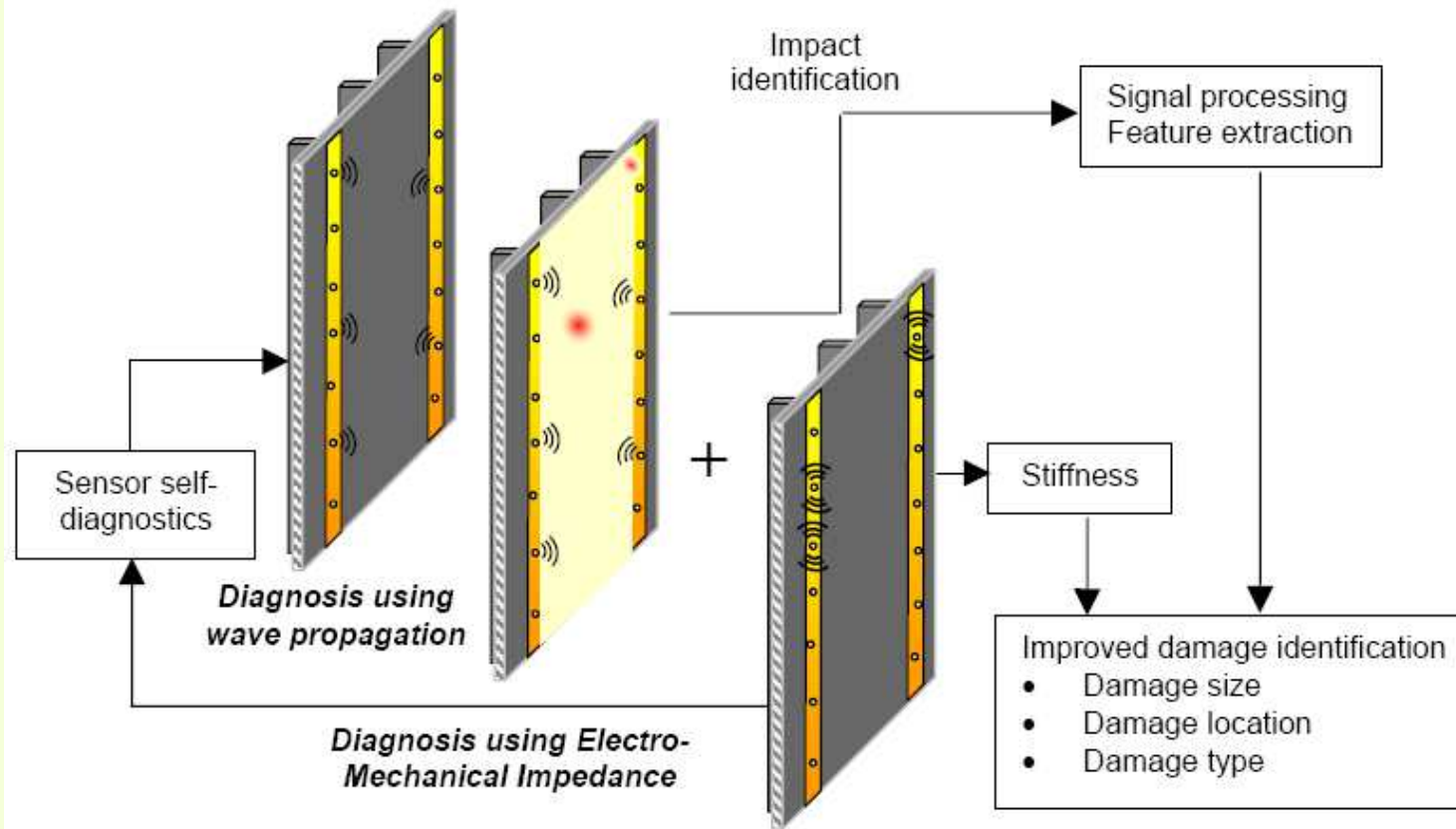
Sensor networks should also be 'fail-safe'. If a sensor fails, the damage identification algorithms must be able to adapt to the new network.

Optimally define the number and location of the sensors; identification of the features sensitive to small damage levels; the ability to discriminate changes in these features caused by damage from those caused by changing environmental and / or test conditions

Better use of the nonlinear response characteristics of the damaged system.

Convincing structural system owners that the SHM technology provides an economic benefit over their current maintenance approaches and convincing regulatory agencies that this technology provides a significant life-safety benefit.

FUTURE TREND: SHM SYSTEM FOR COMPOSITE STRUCTURES

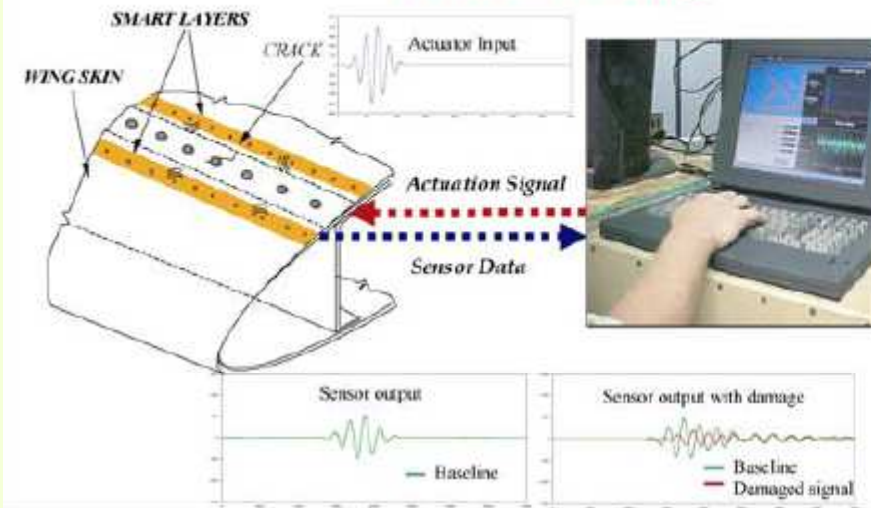


Concept of a dual wave propagation and E/M impedance based SHM

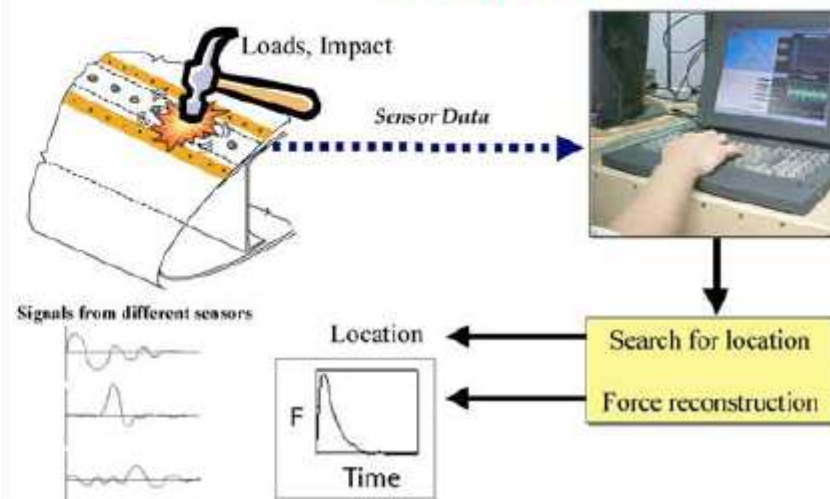
SMART Layer[®] technology: a built-in network of piezoelectric transducers embedded on a thin dielectric carrier film that queries, monitors and evaluates the condition of a structure.

SELF-DIAGNOSTIC SHM SYSTEM FOR COMPOSITE STRUCTURES

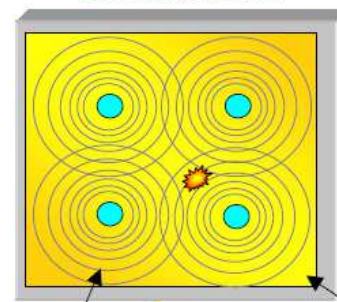
Active Sensing



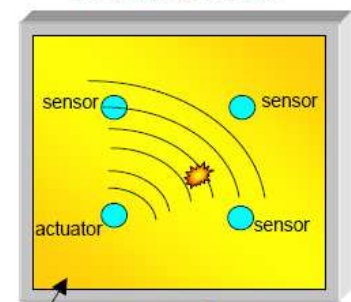
Passive Sensing



E/M Impedance method Local damage detection



Wave propagation method Global damage detection



Radius of detection of each sensor using the E/M method

SMART Layer with piezoelectric elements

Active sensor self-diagnostics
Improved resolution of damage location
Complete coverage of damaged area

Concept of a dual wave propagation and E/M impedance based SHM

Coupling of wave propagation and E/M impedance methods

BENEFITS AND IMPACT OF REAL TIME SHM

- Immediate assessment of instrumented structures
- Allow an optimal use of the structure, a minimized downtime, avoid of catastrophic failures
- Move from Time based scheduled maintenance \Rightarrow Condition/Performance based maintenance
- Optimization of response and recovery
- Reduction of social and economic impacts and costs
- Prolong the service lives of structures while decreasing costs
- Validation of design assumption and FE modeling
- Improve maintenance/management strategy for better allocation of resources
- Assurance of a structure's strength and serviceability
- Study of the performance of different design /construction techniques



RESEARCH PROPOSAL

DAMAGE DETECTION AND CONDITION ASSESSMENT

OF CIVIL ENGINEERING STRUCTURES

USING STRUCTURAL HEALTH MONITORING

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OUTLINE OF THE RESEARCH PROPOSAL

- **STATE OF THE PROBLEM**
- **MOTIVATION OF THE RESEARCH PROPOSAL TOPIC**
- **SCOPE AND OBJECTIVES**
- **METHODOLOGY**
- **REQUIRED FACILITIES AND INSTRUMENTATION**
- **REQUIRED FUND, TIME PLAN, RESEARCH TEAM**
- **ANTICIPATED OUTCOMES AND EXPECTED KEY FINDINGS**
- **CASE STUDY**

STATE OF THE PROBLEM

The 1971 San Fernando, California, earthquake (magnitude 6.7) collapsed four buildings at the San Fernando Hospital, killing 49 people. During the 1995 Hyogoken Nambu Earthquake, a great number of structures suffered various levels of severe damage.

Real-time seismic monitoring of such buildings can provide critical information about their structural integrity/condition and help save lives in future earthquakes.

SHM's target is the ability to detect damage at early stage / monitor the structure throughout its working life in order to reduce maintenance requirements and subsequent downtime.



MOTIVATION OF THE RESEARCH PROPOSAL TOPIC

- The increased size and complexity of recently erected structures have lessened the efficacy of visual inspection.
- Automatic and low-cost structural health monitoring (SHM) system is in high demand and crucial to reduce the costs associated with manual inspection.
- Several bridges are structurally deficient or functionally obsolete, timely detection of the bridge defects and accumulated damage enables infrastructure owners to implement preventive or proactive maintenance .

RESEARCH PROPOSAL SCOPE AND OBJECTIVES

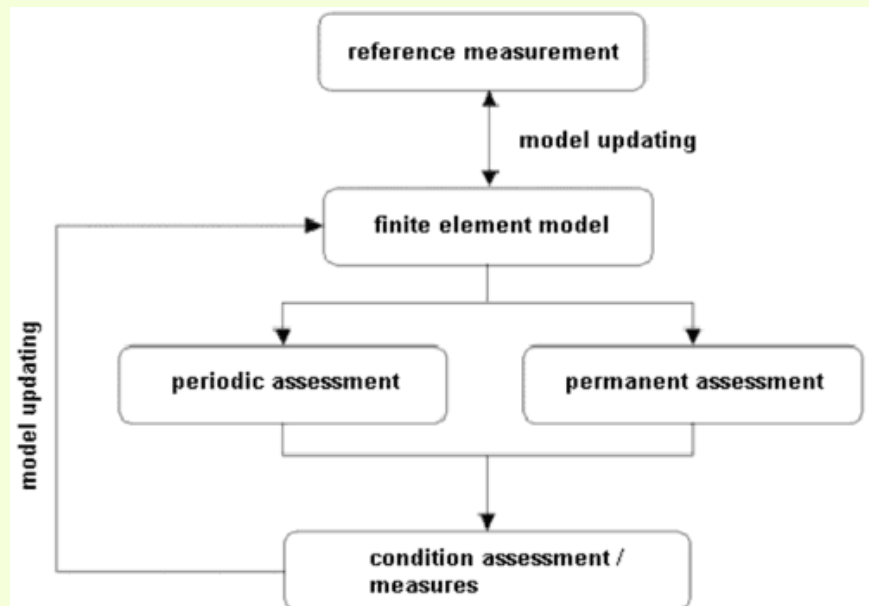
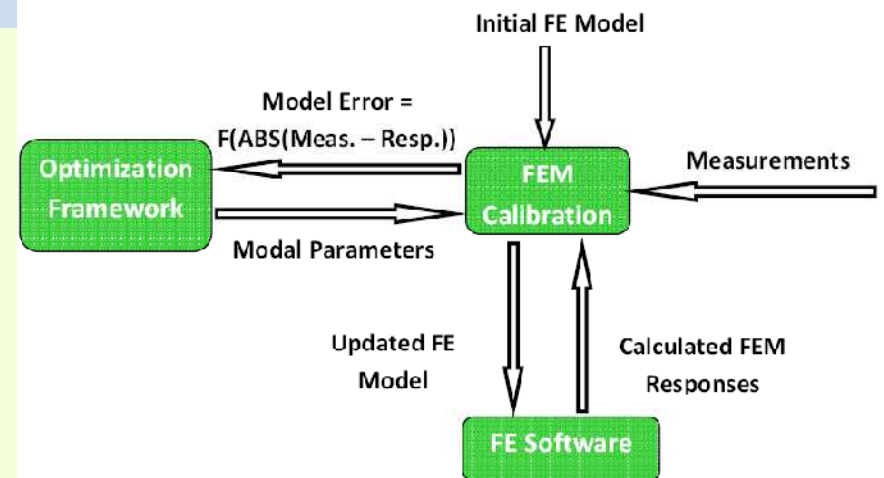
- To optimize and develop a new Structural Health Monitoring (SHM) system suitable for existing and new civil Engineering structures for safe and cost-effective operation.
- To implement an intelligent decision making algorithm to classify and predict the damage in terms of severity to the life and performance of the structure.
- To validate/integrate a vibration-based damage-detection algorithm
- To enable rapid deployment and prioritized inspections of the critical structures;
- Effective use of sensors and broad band digital communications for remote monitoring of structures subjected to dynamic loads;
- To identify and implement effective algorithms for system identification, model updating and damage detection suitable for remote monitoring of structures subjected to seismic forces and condition changes due to deterioration or impact.
- To investigate the performance of an evolutionary strategy in finite element model updating approaches for damage detection purposes

METHODOLOGY (1/3)

Vibration-based damage detection evaluates the global structural condition. The structural damage usually causes a decrease in structural stiffness and an increase in structural damping, thereby producing change in vibration characteristics.

The research projects require implementation of concepts in structural design, finite element analysis, vibrations, digital signal processing, digital image processing, data acquisition systems, control systems and extensive knowledge of sensors and statistical methods.

A finite element model will be created with open FE software detailed design drawings.

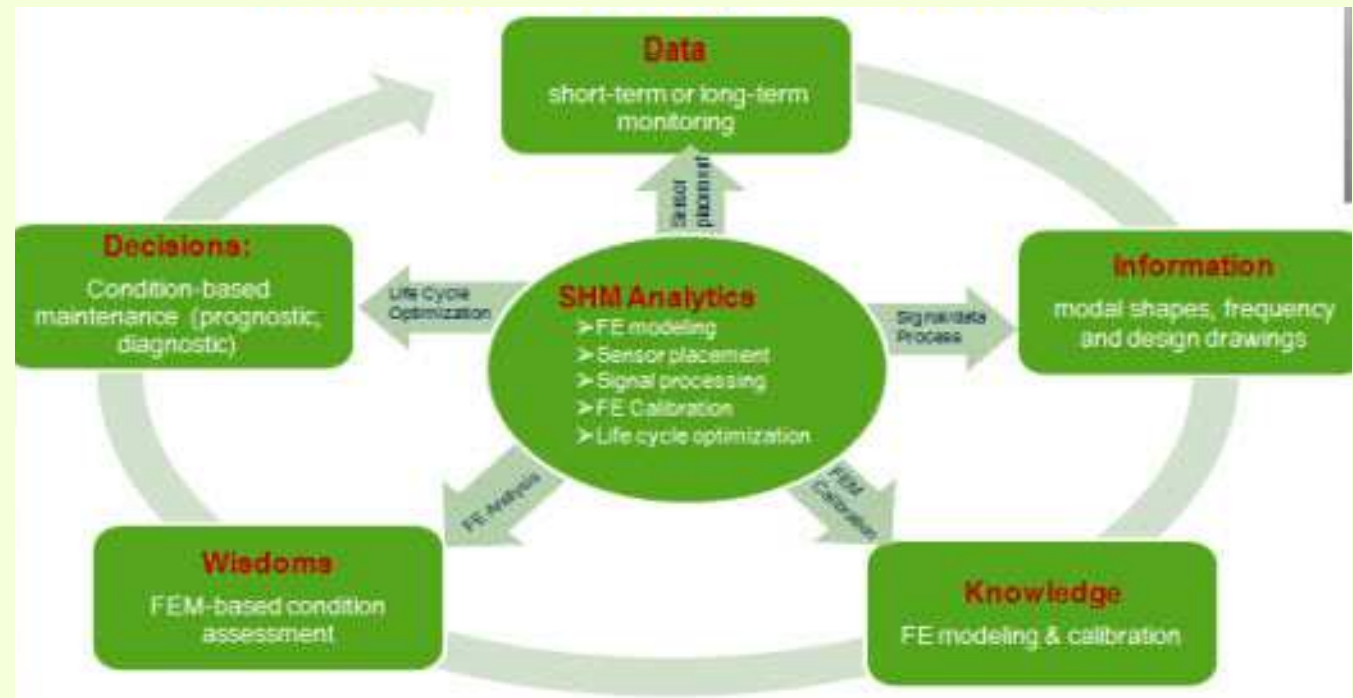


METHODOLOGY (2/3)

The FEM will be used to optimize placement of accelerometers on the bridge to record the dynamic responses

A FEM calibration method was developed using the optimization technology to facilitate the calibration process

The recorded responses will be processed to extract the primary modes and the frequencies used for FEM calibration



METHODOLOGY (3/3)

- (i) The research projects are highly interdisciplinary in nature and require implementation of concepts in structural design, finite element analysis, vibrations, digital signal processing, digital image processing, data acquisition systems, control systems and extensive knowledge of sensors and statistical methods.
- (ii) Numerical modeling and ambient vibration test to characterize the dynamic behavior of the bridge and better design the monitoring system,
- (iii) Installation of the monitoring equipment,
- (iv) Development of software to retrieve the continuously generated data series from the bridge to FEUP and perform the on-line automatic identification of the bridge modal parameters,
- (v) Study of the modal parameters variations to build numerical models suitable to eliminate the effect of environmental and operational variables and finally,
- (vi) Evaluation of the capability of the installed monitoring system to detect realistic damages.

REQUIRED FACILITIES AND INSTRUMENTATION



CompactRIO : Long-Term Continuous Monitoring, GPS receivers to synchronize measurements , Long-term strain/vibration studies, Fatigue monitoring, Stand-alone (embedded data logging, processing), (static and dynamic measurements)

USB and Wi-Fi DAQ: Portable Structural Testing, Structural diagnostics, Load ratings, Short-term testing, PC-based (real-time data streaming to PC host), (static and dynamic measurements)

- **Sensors and Measurements:** strain gages, Piezoelectric accelerometers, linear-voltage differential transformers (LVDTs) and string potentiometers for displacement, tilt, and crack sensors; thermocouples and resistance temperature detectors (RTDs); and environmental sensors.

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REQUIRED FUND, TIME PLAN, RESEARCH TEAM

The required fund could be 25000 \$ for instruments/facilities and software, and 25000\$ for research team

The time plan could be 3 years duration, procurement the required instruments/facilities and software, selection of the critical structures as case study and coordination with administration / owner of the target structures, formulated the Initial FE element based on the design drawings. Design the instrumentation layout and measurements. Based on either ambient or forced excitations, the Modal parameters could be determined, validation/updated of the initial FE model.

6 graduate students (2 for Ph. D. and 4 for M. Sc.) under supervision of the author could carry out this proposal tasks

ANTICIPATED OUTCOMES AND EXPECTED KEY FINDINGS

Improved condition-based maintenance of civil engineering structures

Provide technical support on the design, installation and operations of SHM systems and equipment

Support for integrating SHM systems to the Internet for remote monitoring

Build laboratory demonstration facilities to understand and teach SHM technologies and systems

Integration of vibration-based measurements into current damage-detection algorithms

The baseline updating methods based on vibration measurement and stiffness identification developed in this study can also be applied to existing bridges in the following two ways; one is for establishing the current baseline of the bridge for its future damage detection and deterioration assessment, the other is for assessing the ongoing “health” if a database of similar types of bridges exist for the comparison purposes

CASE STUDY

Risk analysis is used to define the critical elements of the bridge that in need of monitoring, then we identified which sensors were required and where we could place them on the bridge:

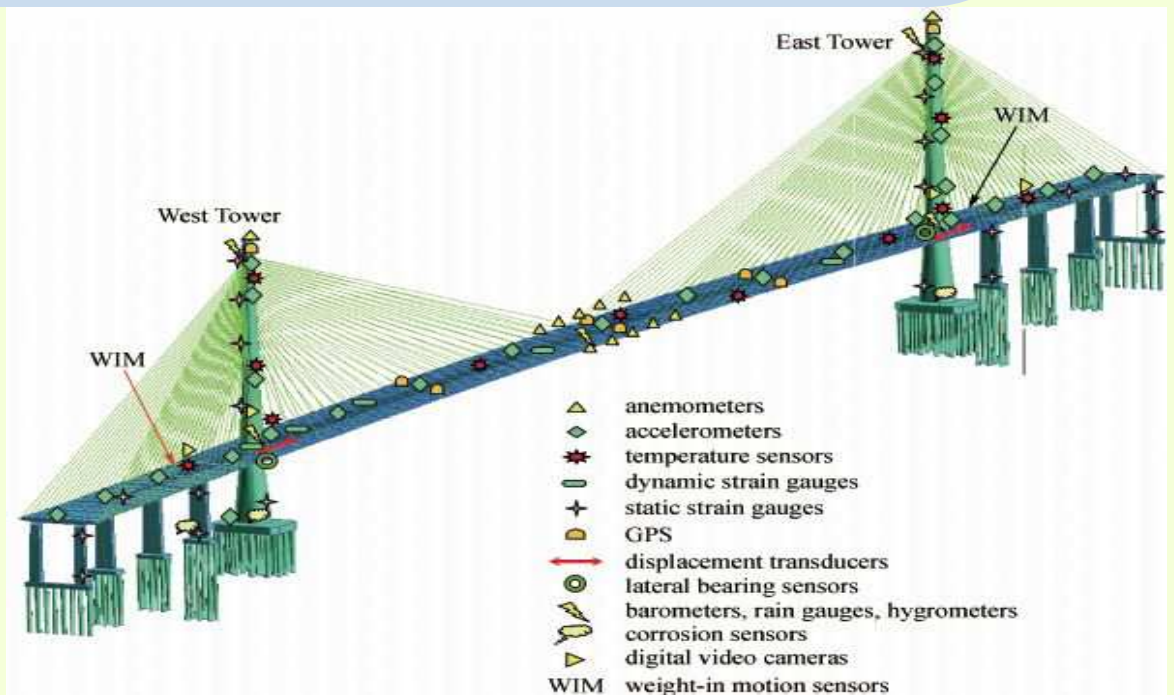
3D accelerometers on the deck, pylons, stay cables, and on the ground to characterize wind movements and seismic tremors
Strain gages and load cells on the stay cables and their gussets

Displacement sensors on the expansion joints to measure the thermal expansion

Water-level sensors on the pylon bases to detect infiltration

Temperature sensors in the deck to detect freezing conditions

Linear variable differential transducer (LVDT) sensors on the stay cables to measure movement, Load cells on the restrainers for recalibration in the event of an earthquake; Two weather stations to measure wind intensity, direction, air temperature, and relative humidity





THANK YOU FOR YOUR KIND ATTENTION

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