Workshop on

EARTHQUAKE RESISTANCE OF LOW-COST ENGINEERED HOUSING IN NORTH-EAST INDIA

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Structural Health Monitoring

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What is Structural Health Monitoring (SHM)

"The process of implementing a damage detection and characterization strategy for engineering structures"

SHM Involves:

- ➢Health monitoring
- ➢Operational Evaluation
- ➢Data Feature Extraction
- ➢Statistical Models Development

Objective of Structural Health Monitoring

- Performance enhancement of an existing structure
- Monitoring of structures affected by external factors
- Feedback loop to improve future design based on experience
- Assessment of post-earthquake structural integrity
- Decline in construction and growth in maintenance needs
- The move towards performance-based design philosophy

Steps of Structural Health Monitoring

Determination of damage existence

↓

Determination of damage's geometric location

↓

Quantification of damage severity

↓

Prediction of remaining life of the structure

Success of ongoing Health Monitoring

Infrastructure	2005	2013
Aviation	D+	D ↓
Bridge	C	C+ ↑
Dams	D	D
Drinking Water	D-	D ↑
Energy	D	D+ ↑
Hazardous Waste	D	D
Inland Waterways	D-	D-
Ports	C-	C ↑
Public Parks and Recreation	C	C- ↓
Rail	C-	C+ ↑
Roads	D	D
Schools	D	D
Solid Waste	C+	B- ↑
Transit	D+	D ↓
Waste Water	D-	D ↑

Grade	Implication
A	Exceptional (fit for the future)
B	Good (adequate for now)
C	Mediocre (requires attention)
D	Poor (at risk)
E	Failing (unfit for purpose)

	2005	2013
Estimated Investment needed	1.6 trillion (by 2010)	3.6 trillion (by 2020)
Overall Condition	D	D+

[http://www.infrastructurereportcard.org/a/#p/grade-sheet/gpa]

Need for Structural System Identification

Deteriorating Infrastructure

Courtesy: Google Image

Worldwide Monitoring Projects

Egnantia Highway - Greece

(source: Ntotsios et al 2009)

Stork Bridge Outdoor Deployment - Winterthur

(source: EMPA)

Fiber Optic sensing system - Sutong Bridge (China)

How to Do SHM in practice?

- Visual Inspection
  - ❖ Fully experience-based
  - ❖ Subjective/Non-quantitative

- Non-Destructive Evaluation (NDE)
  - ❖ Various technologies for different purposes
  - ❖ Demands a high degree of expertise
  - ❖ Time consuming and costly
  - ❖ Usually requires *a priori* knowledge of the potentially damaged region
  - ❖ Works only in accessible regions of the structure
  - ❖ Interruption and downtime
  - ❖ Labour intensive and risky

Current Practice : Visual Inspection

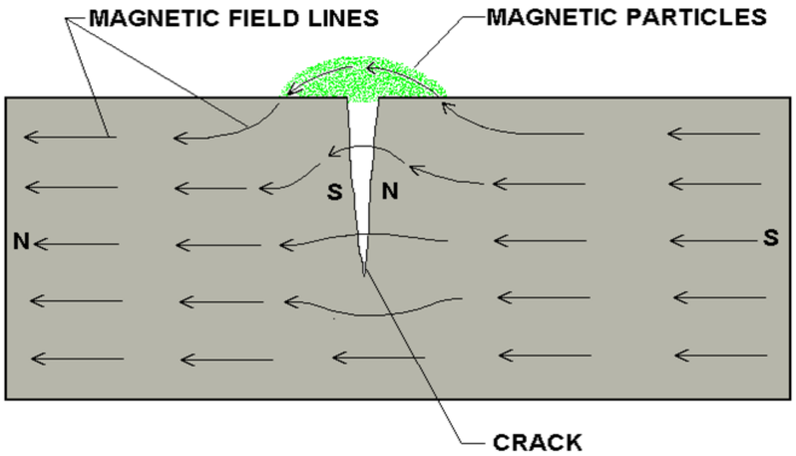




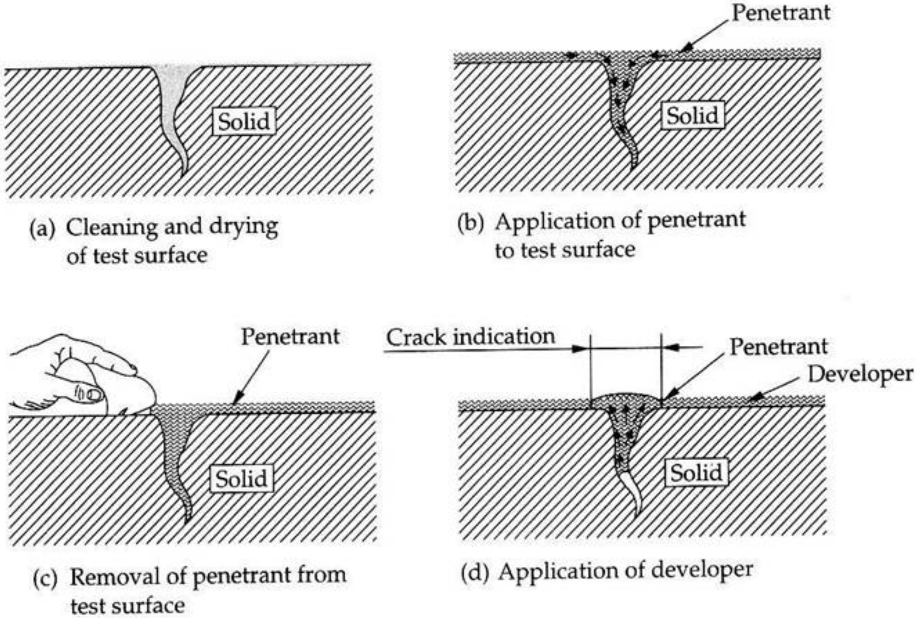

vibration-based methods are gaining popularities in structural health monitoring and damage detection

NDT

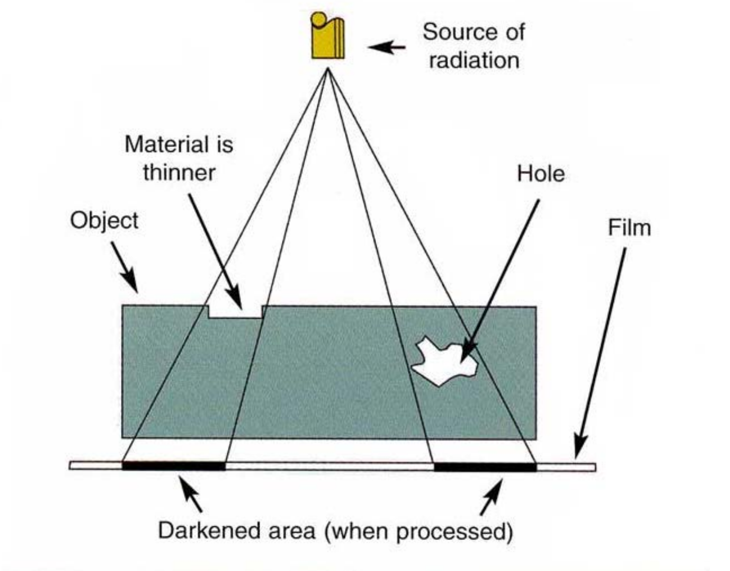
Visual Inspection



Magnetic Particle Testing

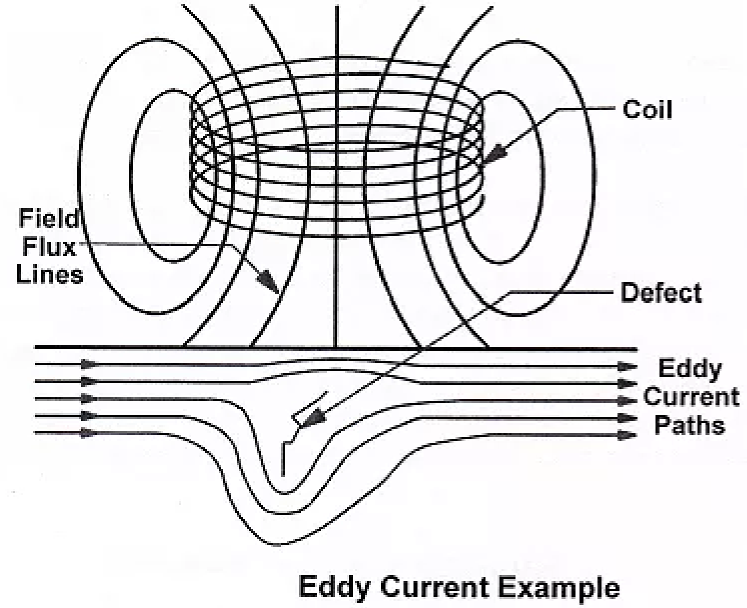


Dye Penetration Test

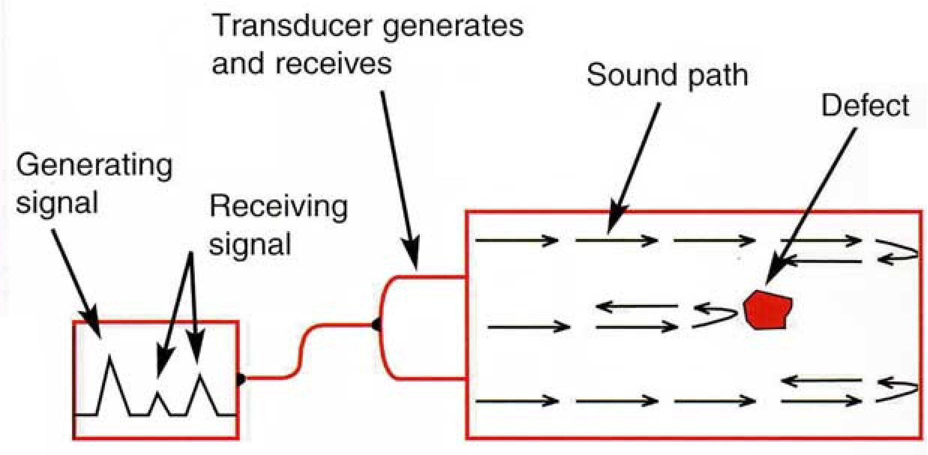


Radiography Test

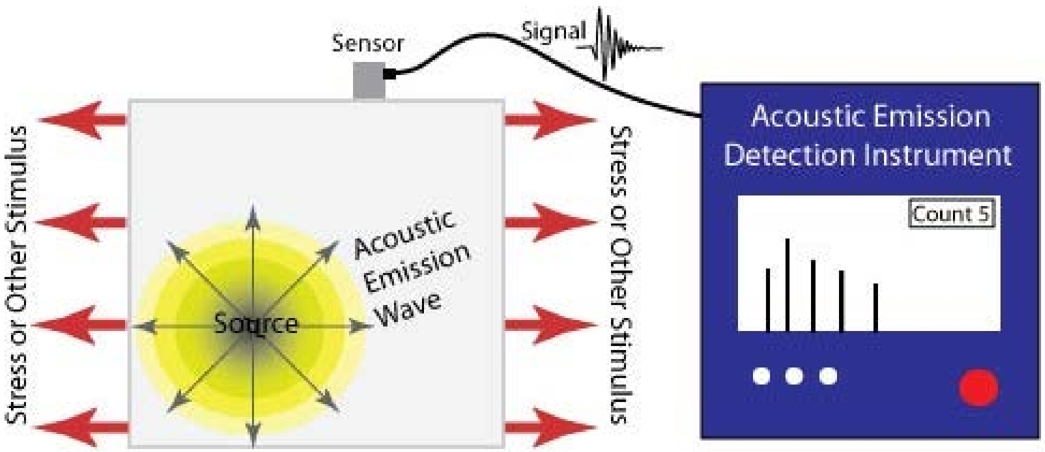
NDT



Eddy Current Test



Ultrasonic Test



Acoustic Emission Test

Thermal Infrared Test

How to Do SHM in practice?

Static-Based SHM

- Based on the premise that damage will alter the static properties of the structure.
  - e.g. displacements, rotations

- Drawback

Considerable static deflection requires large amount of static force

How to Do SHM in practice?

Vibration-Based SHM

- Based on the premise that damage will alter the dynamic properties of the structure.
  - e.g. structural response, frequencies, mode shapes, damping or modal strain energy change

- By measuring the structural response by means of sensors strategically placed on the structure, and intelligently analyzing these measured responses, it is possible to identify damage occurrence.

- It can be done either in modal domain or physical domain

Vibration Based SHM: Sensors

- Different forms of dynamic structural response:
  - Displacement, Velocity, Acceleration, Strain.
  - Which ones to measure depends on monitoring conditions and objectives.
- Sensing technology: an ever emerging field of study
- Based on what to measure, different sensors available:
  - Laser Displacement Sensors (LDS)
  - Velocity Transducers
  - Seismometers
  - Piezoelectric Accelerometers
  - Strain Gauges
- Most of these sensors can be wirelessly connected

Collection of Sensory Information

Load Cell (Force)

LVDT (Displacement)

Accelerometer (Acceleration)

Strain Gauge (Strain)

Vibration Based SHM: Sensors

Pros and cons of various types of sensors:

- Bandwidth:
  - displacement sensors capture low frequency modes
  - acceleration sensors capture high frequency modes
- Global vs. Local:
  - strain gauges capture local dynamics better
  - accelerometers/displacement sensors measure global dynamics

Vibration Based SHM: Model-Based Techniques

* Based on a model (e.g. F.E.) of the monitored structure.

* Optimization based methods:

- An initial model is updated using measured structural response. Also called FE model updating
- Optimization algorithms are run by iteratively changing the values of some structural properties (e.g. Young's modulus), so that the FEM parameters match measured parameters.
- Measured parameters: Measured responses or some parameters obtained from measured responses (e.g. modal properties).
- Usually require repeatedly solving the forward problem.

Vibration Based SHM: Model-Based Techniques

Alternatively, inverse problem solution approach:

- Identify modal parameters using some system identification method.
- Use identified modal parameters to obtain physical parameter (mass, damping, stiffness) matrices.
- Does not require repeatedly solving the forward problem, but is more complicated.

Vibration Based SHM: Model-Based Techniques

- PROS:
  - Allow damage detection, as well as damage location and extent estimation. May even be used to assess the damage type and to estimate the structure's remaining life, though research is still at its onset in this regard
- CONS:
  - Require high user expertise
  - Affected by modelling assumptions (e.g. boundary conditions, number of DOFs, material properties, etc.)
  - Often too many unknowns
  - Usually computationally expensive

Vibration Based SHM: Data-Based Techniques

Data-Based techniques are based on statistical, rather than physical models of the structure. These methods are called *data*-based because the features extracted from the structural response are obtained by simple operations performed on the response time histories itself, and do not require any physical model assumptions. These approaches are often said to "let the data speak by themselves".

Vibration Based SHM: Data-Based Techniques

PROS

- Do not require high user expertise.
- Often coined using machine learning knowledge: highly computationally efficient and ideal to be automated.
- Take into account uncertainties inherently present in SHM.
- Free from modeling assumption induced errors.

CONS

- Without a physical model, can at most reach the second level of the damage detection hierarchy (damage location).
- Being based on a statistical model of the features, they require sufficient data to be available.

Vibration Based SHM: Uncertainties

Many sources of uncertainty in the different stages of SHM:

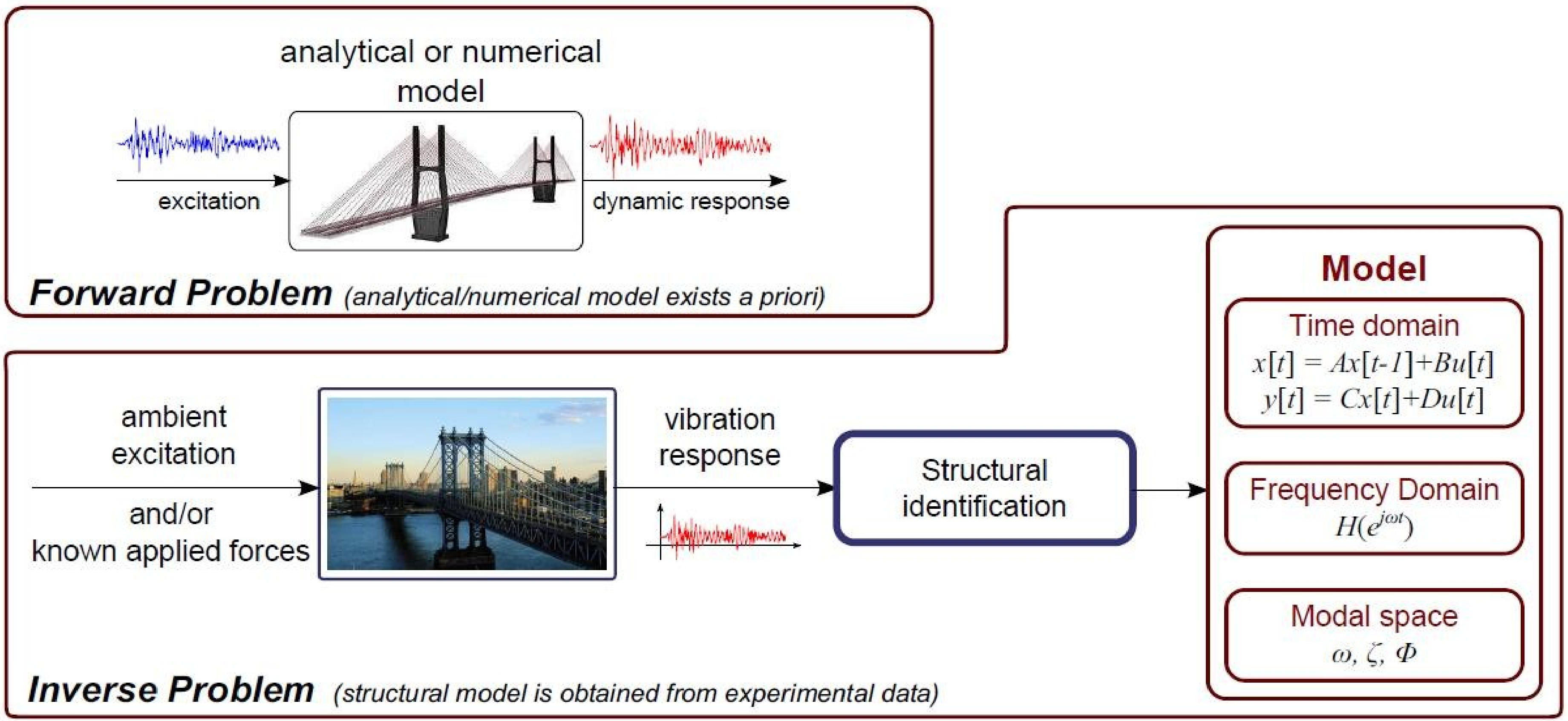
During data acquisition:

- Measurement noise,
- Environmental effects (different temperature, humidity levels),
- Unknown and nonstationary inputs (traffic, wind, earthquake; may excite different frequency regions),
- Missing data (not every point on the structure observed).

During feature extraction/modeling/identification:

- Modeling assumptions,
- Errors associated with any numerical method,
- Non-unique identification (many models may fit the measured data equally well).

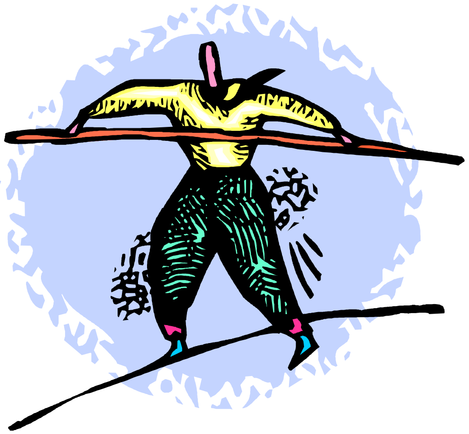
SHM by Structural System Identification



Courtesy of Prof. E. Chatzi, ETH

Structural Monitoring Challenges

- Infrastructure is expected to provide:
  - reliable service for long periods of time,
  - Undergoing major technology changes,
  - spanning several generations and experiencing dramatic evolutions
- Develop Wireless Sensor Networks
  - Reliable
  - Energy aware
  - Smart



Some Barriers in SHM 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.

Monitoring Metrics

Measure:

- Acceleration
- Strain
- Climatic Conditions
- Curvature
- Displacements
- Load
- Tilt/Slope
- Scour

Identify

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

Smart Sensor concept

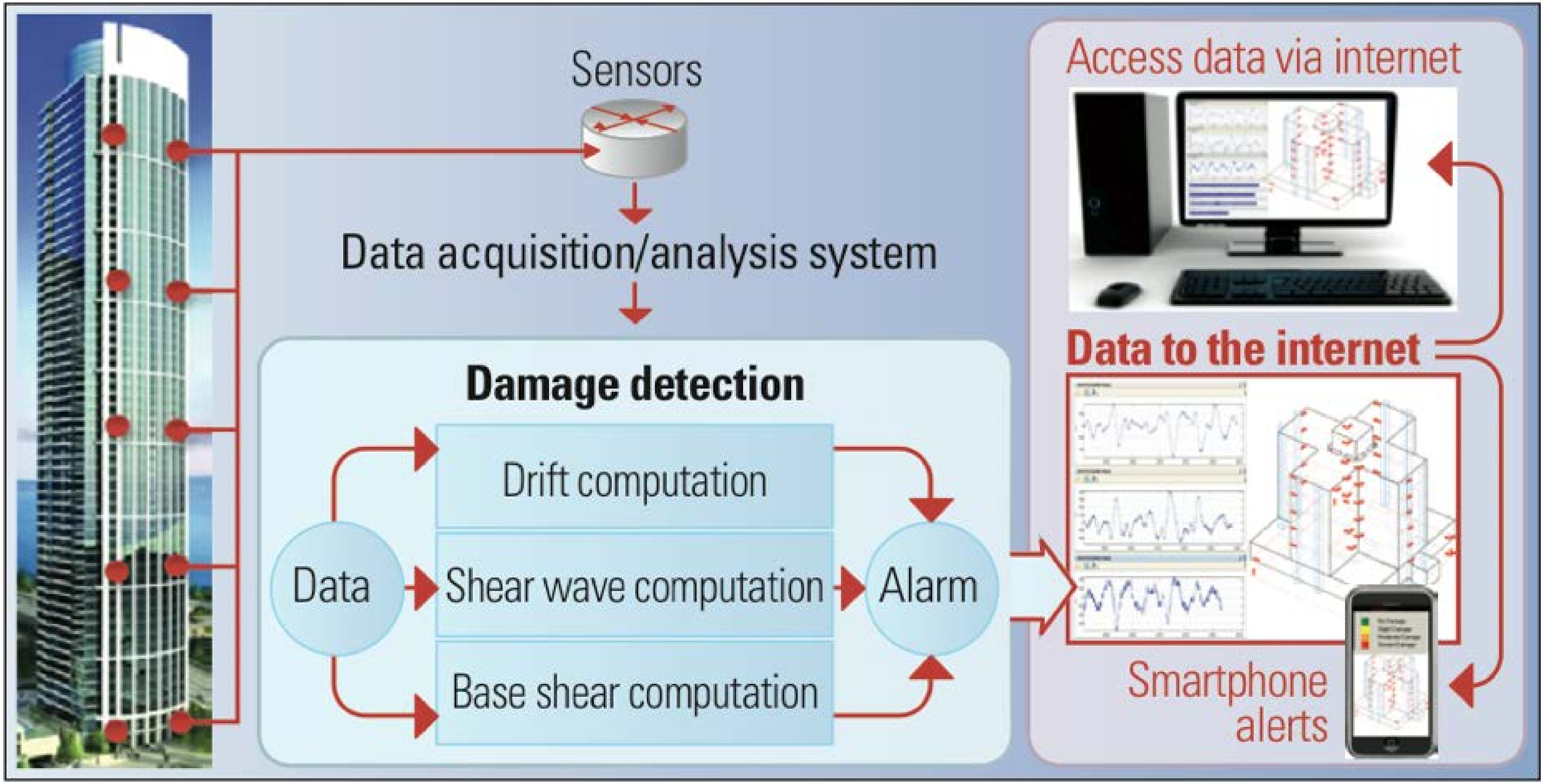
Earthquake Event

Sensors Wake-up (unique IDs)

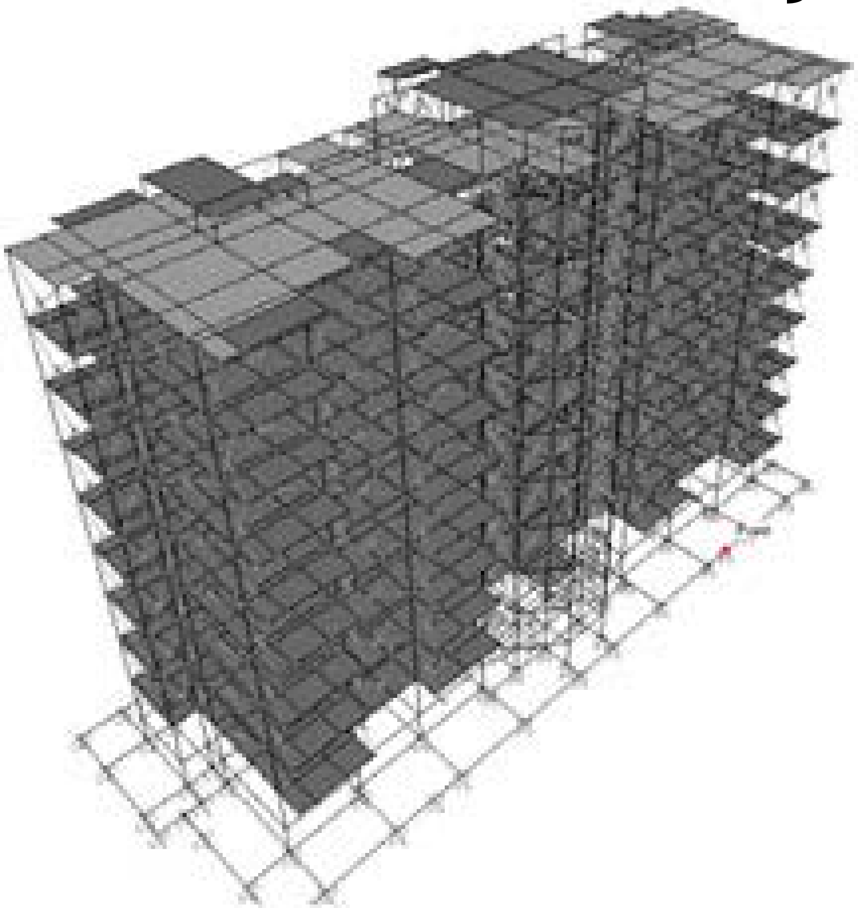
Events Recorded and stored in BS

Sensors go back to sleep

Future of SHM



Study-1: G+8 storey RCC BSNL building in Guwahati (Borsaikia, Dutta, Deb 2011)



- 1st Earthquake (11th Feb,2006) –Depth 33 Km in Arunachal Pradesh-Tibet Border.
- 2nd Earthquake (12th Aug,2006) –Depth 66 Km in India-Bangladesh Border.

Study-1: G+8 storey RCC BSNL building in Guwahati (Borsaikia, Dutta, Deb 2011)

2 triaxial force balance in ground and top floor, 4 uniaxial accelerometers in 1st, 3rd, 7th and top in shorter direction and 3 uniaxial accelerometers in 1st, 5th and top of longer direction.

- Damage has been localized using Parametric State Space Modeling.
- Stiffness of Each storeys has been computed.

Study-2: Milikan Library, CalTech (Clinton et al 2006)

The current (2006) forced vibration fundamental frequency of east–west is 22% and of north-south is 12% lower than that originally measured in 1968

- forced vibrations using varying forces.
- minor earthquake shaking.
- weather conditions (rain and wind events, extremes in temperature)

Plan dimension is 21m × 22.9m and height from basement is 48.9m

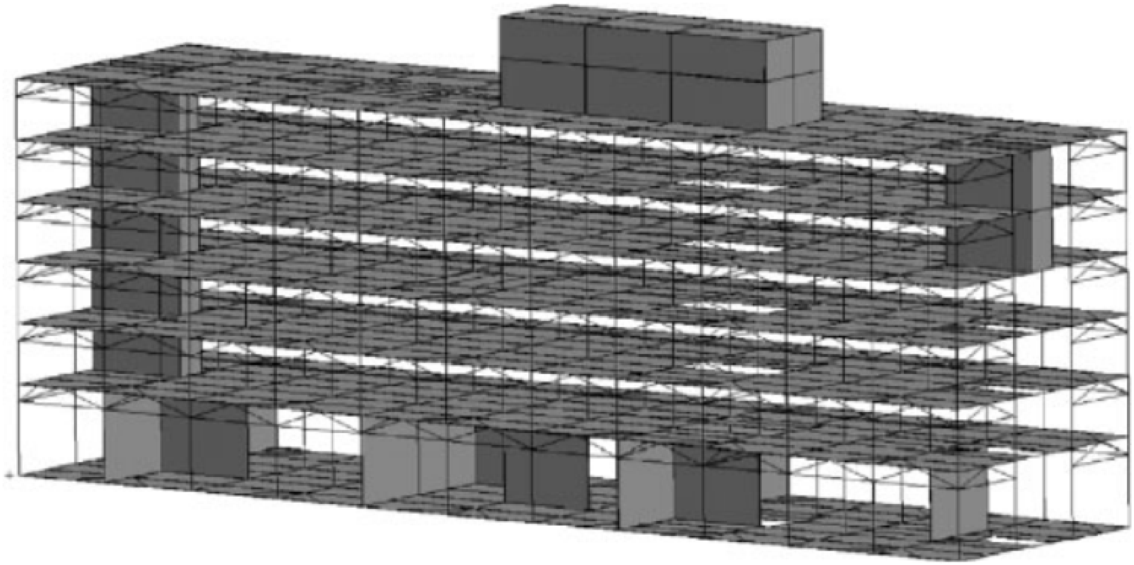
Sensors are densely mounted on the building and these are continuously monitored

Study-3: Long Beach Public Safety Building (LBPSB), California (Chassiakos et al 2006)

- Six storey rectangular steel building built in 1950s, having plan dimension of 82.3m × 21.3m.
- Due to 1994 Northridge earthquake this facility need significant seismic mitigation measures.
- So health of this structure was monitored and it was retrofitted.
- The ambient vibration data collected before, during, and after the structural retrofit.

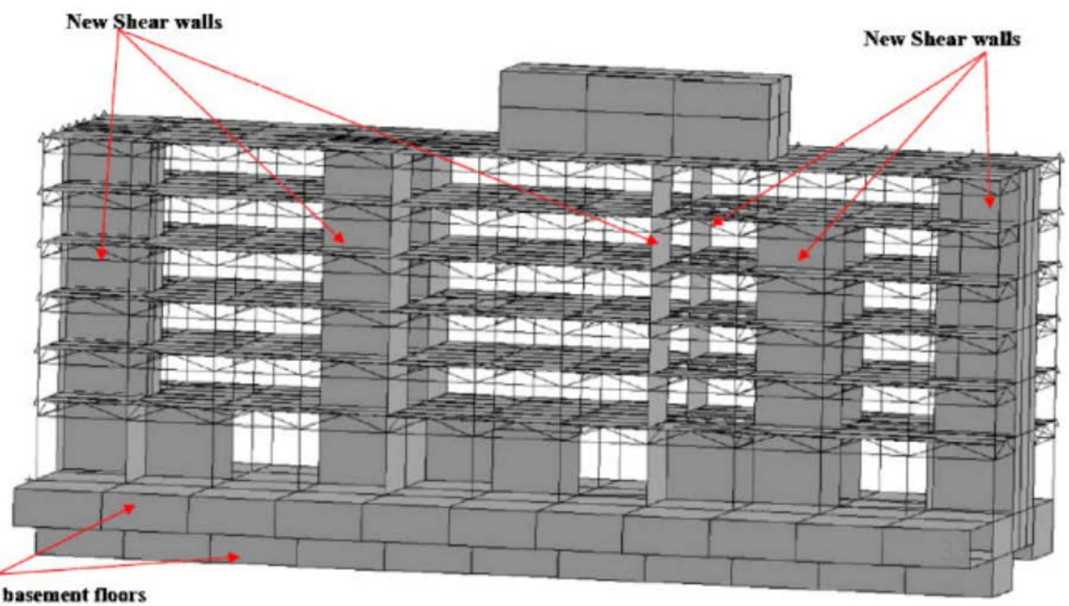
Mode	Freq before Retrofit	Freq after Retrofit	% change
1	0.94 Hz	2.09 Hz	122.34 %
2	1.20 Hz	2.52 Hz	110.00%
3	1.47 Hz	2.87 Hz	95.24%
4	3.00 Hz	5.21 Hz	73.67%
5	4.25 Hz	7.60 Hz	78.82%

Study-3: Long Beach Public Safety Building (LBPSB), California (Chassiakos et al 2006)



Finite element model of pre-retrofit Long Beach Public Safety Building

Finite element model of post-retrofit Long Beach Public Safety Building.

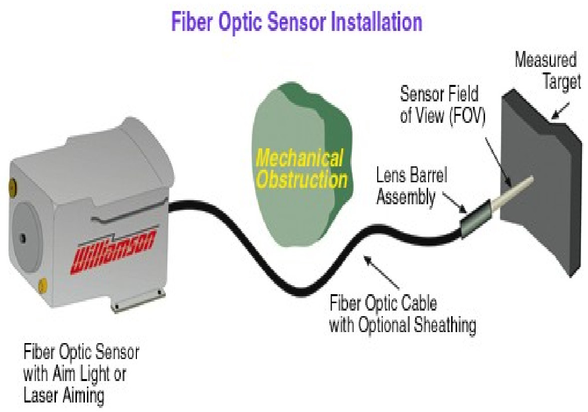


Application of SHM in ‘Housing for All’ Project

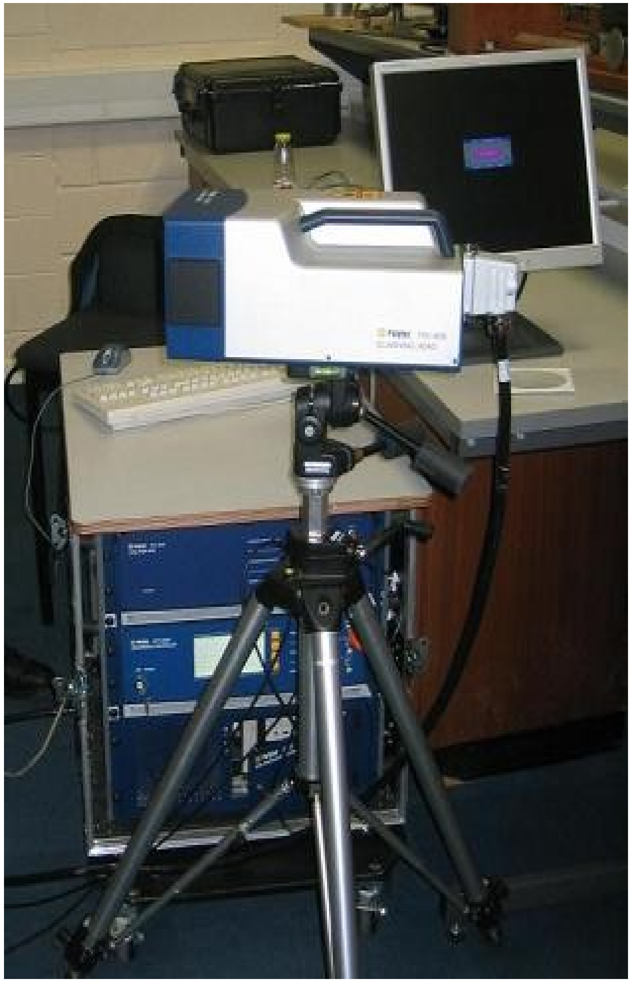
- North-East India is prone to earthquake hazards
- So monitoring is important to reduce seismic hazard
- Proposed Idea: One house will be properly instrumented among a colony of houses
- Sensor data will be taken once in a year and the health of that colony can be estimated
- Visual inspection and NDTs will be done in a regular basis
- This will also be used for post-earthquake health assessment and validate retrofitting operations

Thank You

Sensor Technology



Fibre Optics

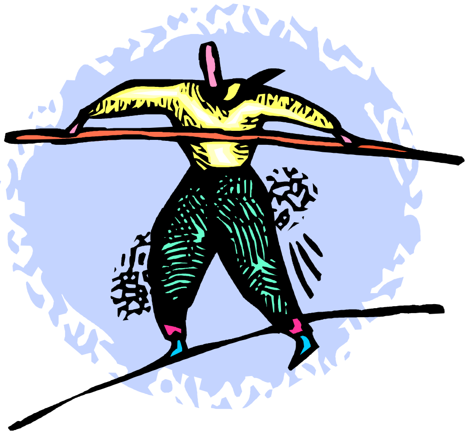


Laser Vibrometer

Ultrasonic Sensor

Structural Monitoring Challenges

- ❑ Develop Design-to-service Solutions
  - ❖ Efficient Monitoring
  - ❖ Digital Signal Processing strategies
  - ❖ Evaluation Criteria
  - ❖ Knowledge bases
- ❑ Develop Smart Control Units
  - ❖ Real-time Feedback
  - ❖ Centralized (or not)



Technological Solutions

- Wireless Sensors
  - Accelerometers/Inclinometers etc
- Laser Scanning
- RFIDs (Radio Frequency Identification)
- Acoustic Emissions
- MEMS (Micro-Electro-Mechanical Systems)
- Increase of Computation capabilities
- Fiber technologies