



Applications of Structural Health Monitoring Technology in Asia

By

**Soh Chee Kiong
Annamdas Venu Gopal Madhav
Bhalla Suresh**

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OUTLINE

1. Introduction

- Infrastructural Developments in Asia

2. Case Studies of SHM of Civil Infrastructures in Asia

- Russia, UAE, Japan, China, India and Singapore

3. SHM Research at CEE, NTU

- Health Monitoring
- Energy Harvesting

4. Summary



1. Introduction



1. Introduction

- Asia is the largest and most populous continent in the world:
 - 45 million square kilometers of land mass (about 30% of world's total)
 - 4.5 billion people (about 60% of world's total).
- It has 49 countries:
 - rich like Japan,
 - poor like Afghanistan
 - densely populated like Singapore.
- SHM is a non-issue for the poor but crucial for the rich and densely populated
- Application of SHM technology in Asia is expected to grow rapidly in pace with its economic growth
- Asia is the world's fastest growing economic region and the largest continental economy by GDP PPP .
- Asia is the site of some of the world's longest economic booms
- The boom is expected to continue with recent launch of the Asian Infrastructure Investment Bank (AIIB).

Infrastructural Developments in Asia: some examples

(Nearly three quarters of today's 50 tallest skyscrapers in the world are located in Asia.)



Dubai : 1990's - 2010



Kuala Lumpur 1990 – 2015



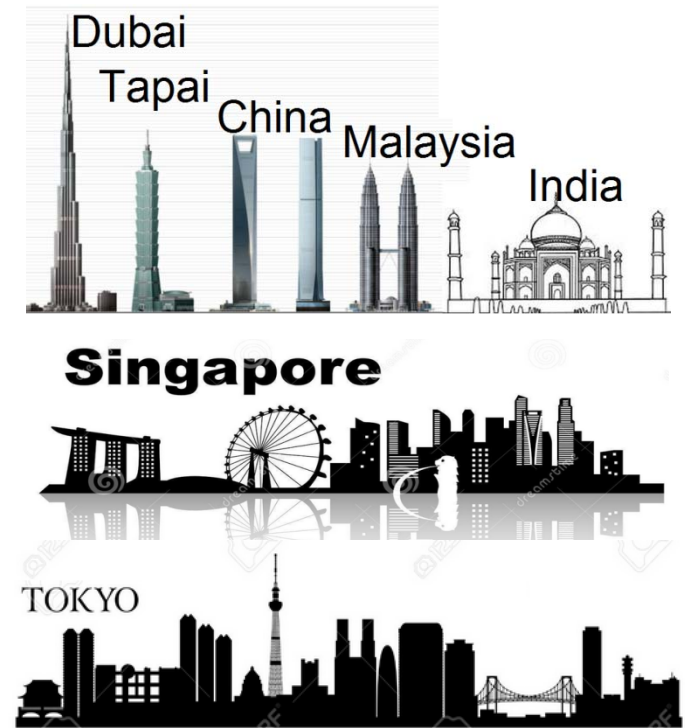
Shanghai : 1990's, 2015



Singapore 1970 - 2015

Infrastructural Developments in Asia

- Civil infrastructures differed due to socio-economical and geographical regions.
- Civil infrastructures varied from country to country, and even from province to province with in the same country.
- Government policies, cultural practices, economy, and budget allotment decides the NDT and SHM practices



Courtesy: 1worldglobes.com, Google search, Dreamstime.com

SHM of different civil infrastructures differed because no two structures are common due to the different soil and environmental conditions.

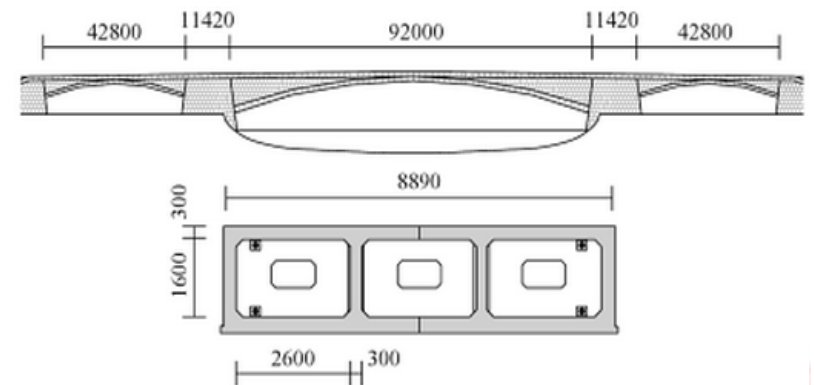
2. Case Studies of SHM of Civil Infrastructures in:

- 1) **Russia - vintage bridge**
- 2) **Dubai - world's tallest building**
- 3) **Japan - suspension bridge**
 - tall building on reclaimed land
- 4) **China - tall tower**
- 5) **India - post earthquake structures**
- 6) **Singapore - link bridge between Singapore and Malaysia**
 - tall structure
 - deep excavation support structure

2. Case Studies of SHM of Civil Infrastructures in: Russia - monitoring of vintage bridge

Bolshoj Moskvoretsky Bridge, Moscow, Russia

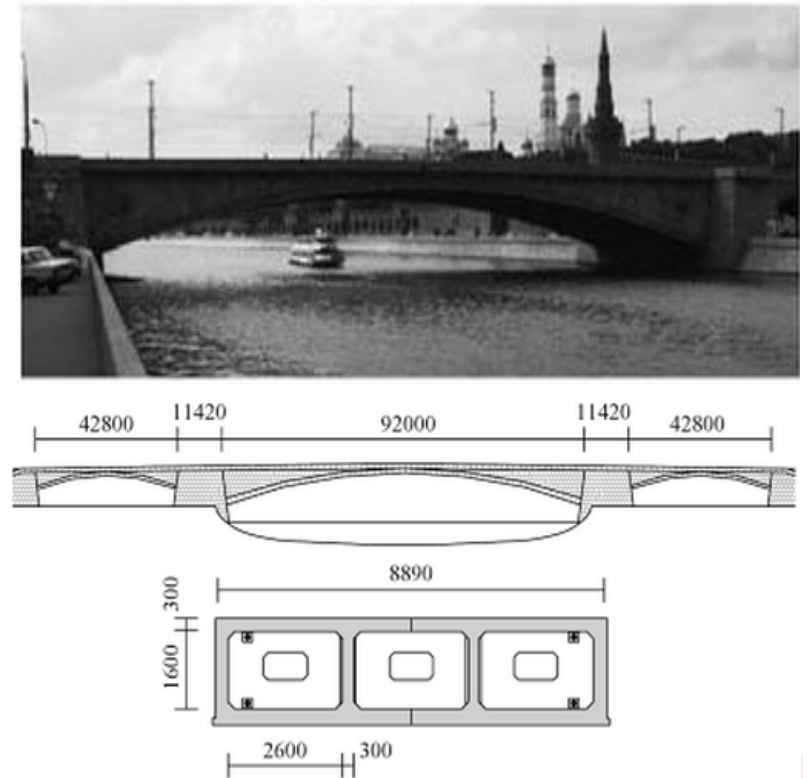
- Constructed over Moskva River in 1936-37
- Located in Moscow, next to Kremlin
- Reinforced concrete arched box girder bridge
- Leads main traffic lines to Red square
- Russian Govt. declared it as a functioning architectural heritage
- Age of structure : >70 years, (Structure Category : Historical Importance)
- Total length: 250m, 3 Spans, 43 + 92 + 43 m . 3 parallel arches
- Cross – section of each arch contains 3 boxes separated by partitions 350 mm - 450 mm thick (along axis of the bridge and diaphragms)
- Super structures consists of bridge deck supported by columns that rest on separating partitions.



Helmut Wenze (2009) Health Monitoring of Bridges,
John Wiley & Sons. ISBN 9780470031735

2. Case Studies of SHM of Civil Infrastructures in: Russia - monitoring of vintage bridge

- SHM started : July 2003
- No. of sensors installed: 22
- Instrumentation designed by: SMARTEC SA, SWITZERLAND and ZAO Triada Holdings, Russia
- Type of sensors : 16 Standard SOFO Sensors in central arch plus 6 thermocouples
- Monitoring target: To continuously monitor temperature, and average strain along horizontal and vertical directions .
- Condition of structure at the beginning of SHM:
 1. Settlement of an abutment producing cracking of the stone lining and structural element.
 2. Chloride penetration into the structure leading to reinforcement corrosion



Helmut Wenzel (2009) Health Monitoring of Bridges,
John Wiley & Sons. ISBN 9780470031735

2. Case Studies of SHM of Civil Infrastructures in: Dubai - monitoring of world's tallest building

Burj Khalifa Tower



Burj Khalifa is 828m tall with more than 160 stories

It holds several world records such as

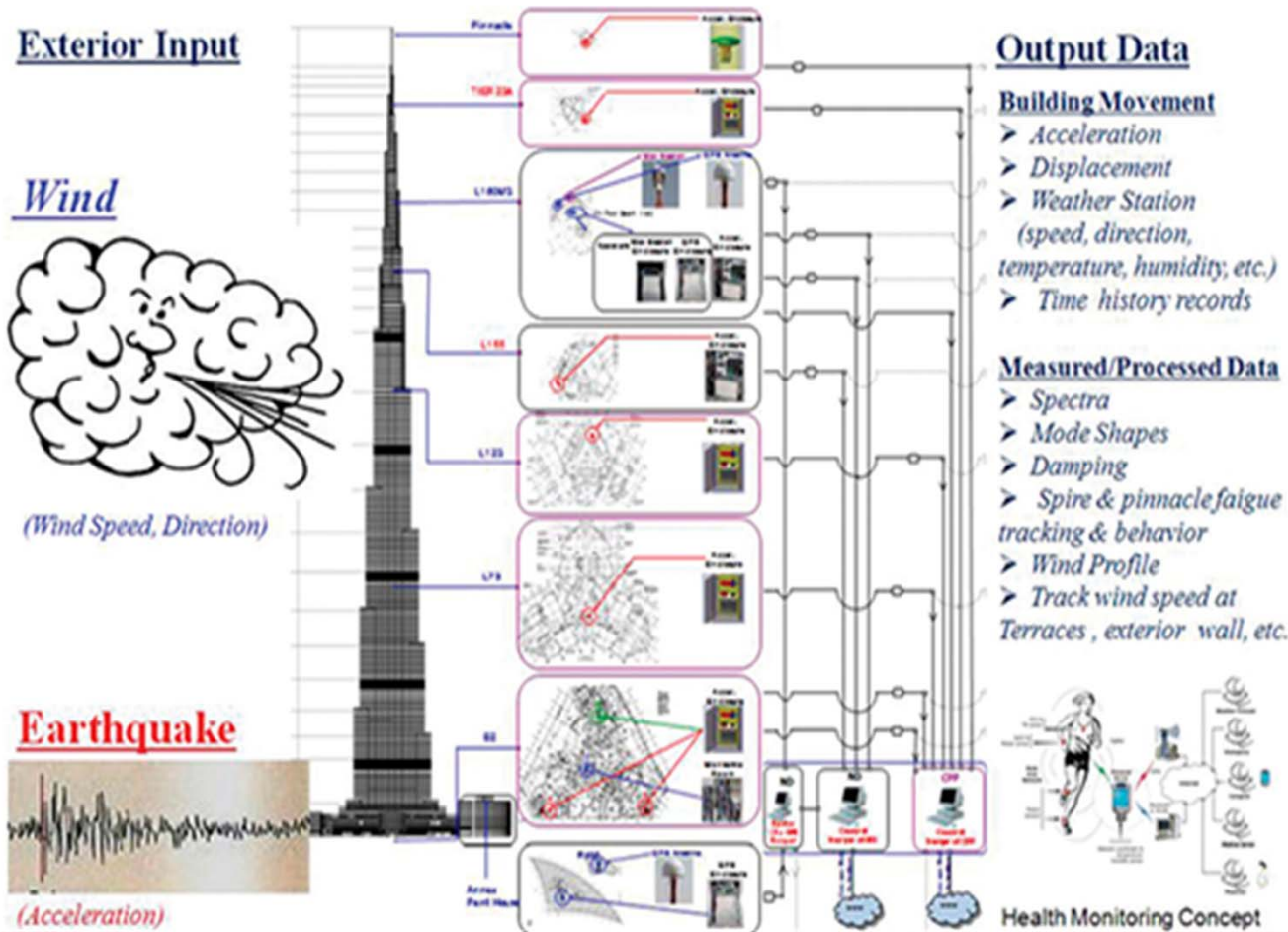
1. tallest building in the world,
2. tallest free-standing structure in the world,
3. highest number of stories in the world,
4. highest occupied floor in the world,
5. highest outdoor observation deck in the world,
6. elevator with the longest travel distance in the world, and
7. tallest service elevator in the world.

First started with temporary SHM system
Now installed with permanent SHM system

2. Case Studies of SHM of Civil Infrastructures in: Dubai - monitoring of world's tallest building

Permanent real-time SHM system

Burj Khalifa: Structural Health Monitoring Program Concept



2. Case Studies of SHM of Civil Infrastructures in: Dubai - monitoring of world's tallest building

Permanent real-time SHM system consists of

- 1) 3 pairs of accelerometers at the foundation level of the tower to capture base accelerations;
- 2) 6 pairs of accelerometers at levels 73, 123, 155 (top of concrete), 160M3, Tier23A, and top of the pinnacle to measure the tower acceleration simultaneously at all levels;
- 3) a GPS system to measure the building displacement at level 160M3;
- 4) 23 sonimometers at all terrace and setback levels, including the top of the pinnacle at over 828 meters above ground, to measure wind speed and direction;
- 5) a weather station at level 160M3 to measure wind speed and direction, relative humidity and temperature.
- 6) Permanent SHM program is an extension to the earlier temporary SHM system.

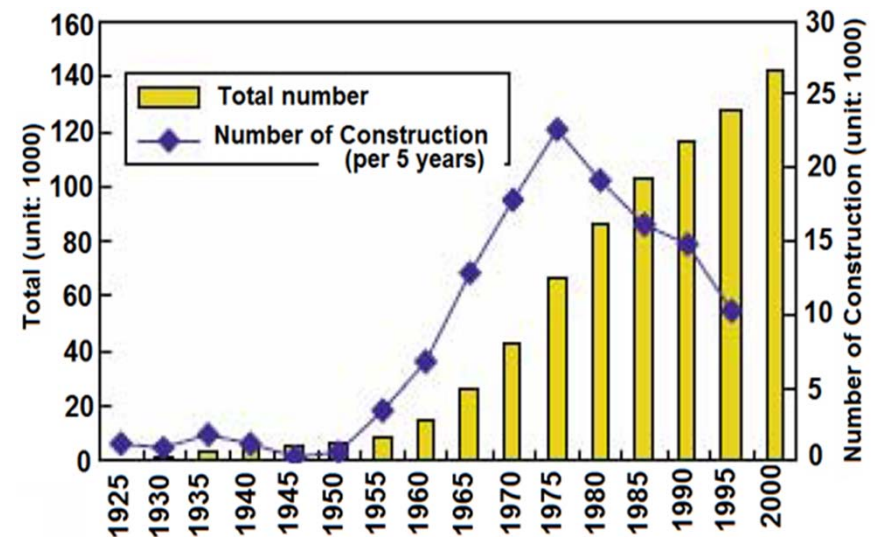
Key system characteristics are:

- 1) acceleration at all levels;
- 2) displacements at level 160M3;
- 3) wind speed and direction at all terraces
- 4) building frequencies, including higher modes;
- 5) estimated building damping ratio at low amplitude due to both wind and seismic events; and
- 6) time history records at the base of the tower due to seismic events.

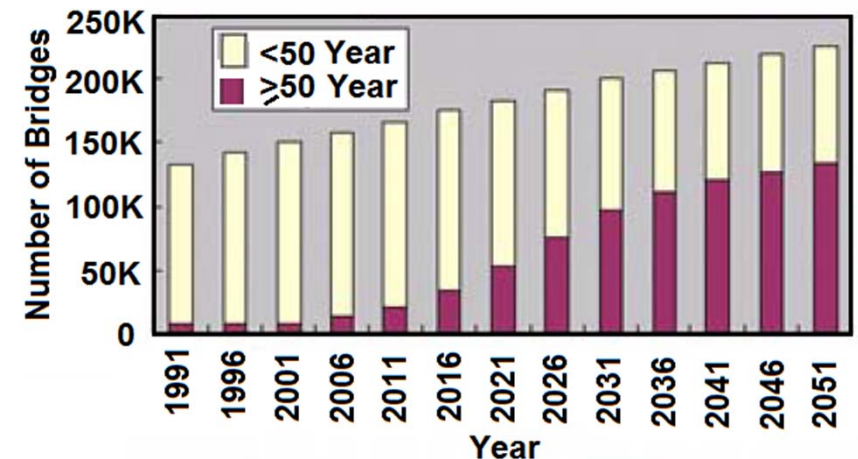
2. Case Studies of SHM of Civil Infrastructures in: Japan - monitoring of suspension bridge

Hakuchō Bridge, Japan

- Japan transportation infrastructure is mainly built post-WWII.
- Japan rapid economic growth between 1955 and 1975 saw increased construction activity.
- After 1950s, there are approximately 650,000 bridges of 1,150,000 km constructed in a 370,000-square kilometer of country area.
- Massive infrastructure network provides essential services to support sustainable economic growth, productivity, and well-being of the nation.



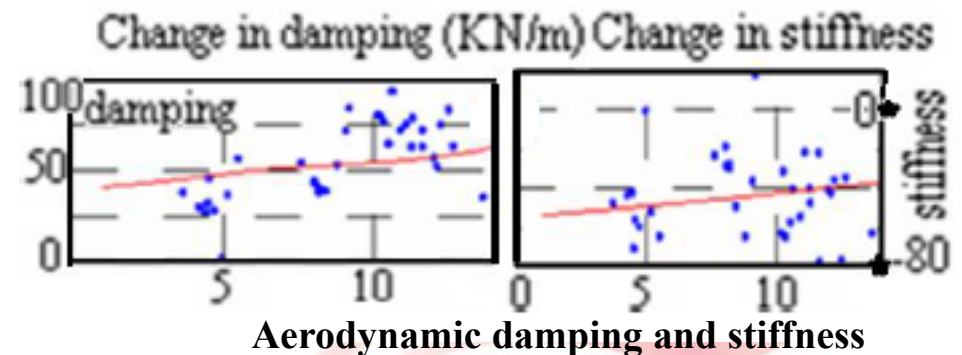
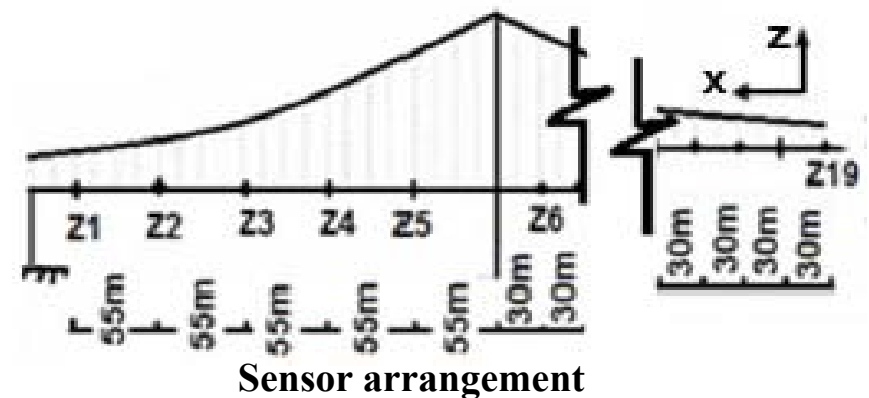
Total number of highway bridges and construction year in Japan.



2. Case Studies of SHM of Civil Infrastructures in: Japan - monitoring of suspension bridge

Hakuchō Bridge, Japan

- Hakuchō Bridge is a suspension bridge in Muroran, Hokkaido, Japan.
- Opened on April 17, 1998
- Main span of 720 meters installed with sensors placed at locations Z1 to Z19,
- The main objective of monitoring is to determine the relationship between the aerodynamics and the bearing friction forces.



2. Case Studies of SHM of Civil Infrastructures in: Japan - monitoring of tall building on reclaimed land

Toyosu, Tokyo, Japan

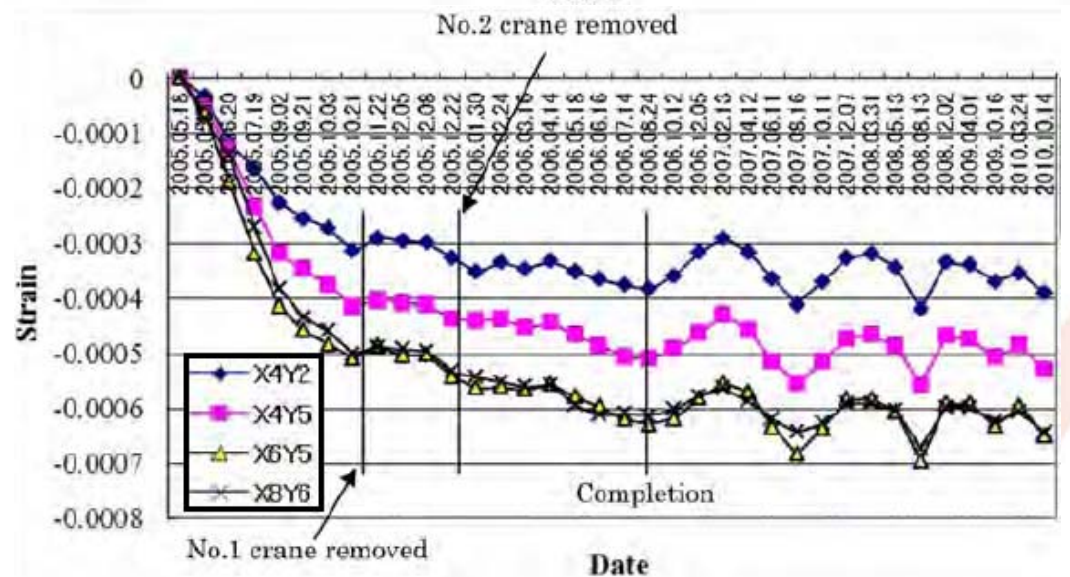
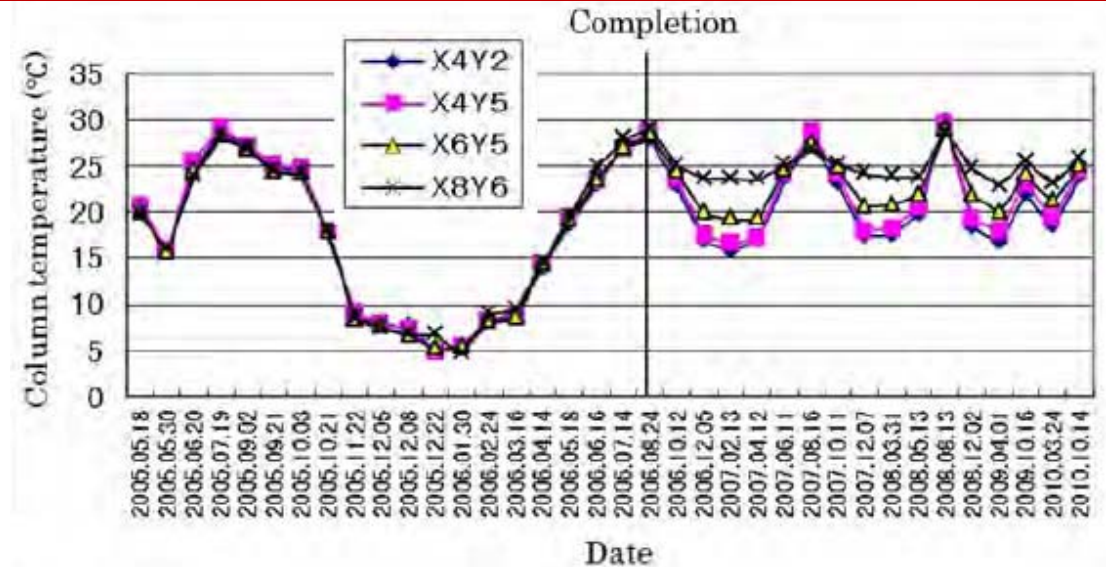


- Toyosu area- land reclaimed from Sea
 - 33-floors tall building : 147m
 - Objective of SHM: Evaluate post-earthquake/ strong wind/ ground sinking
 - Long gage length fiber optic sensor system (known as SOFO) was adopted.
 - Construction period 2004-06
 - Monitoring period: May 2005-October 2010
-
- SOFO sensors were installed on the second floor comprising of 33 steel columns (it was a machinery room 57m x 50m)
 - 5 representative steel columns were monitored
 - Each column was monitored by 1 sensor at centre
 - Dominant load on each column was axial load
 - Sensor length was 1 m (decided based on column height and on-site conditions)

2. Case Studies of SHM of Civil Infrastructures in: Japan - monitoring of tall building on reclaimed land



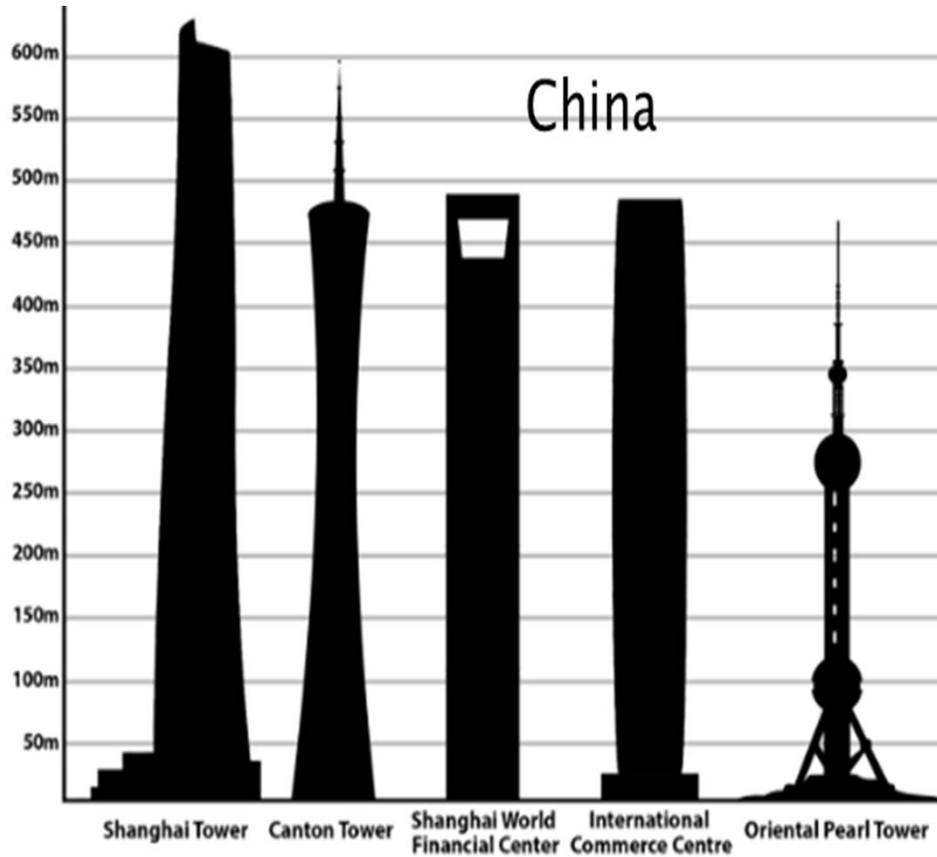
Sensors on representative column



X and Y represent Longitudinal and Transverse directions

2. Case Studies of SHM of Civil Infrastructures in: China - monitoring of tall tower

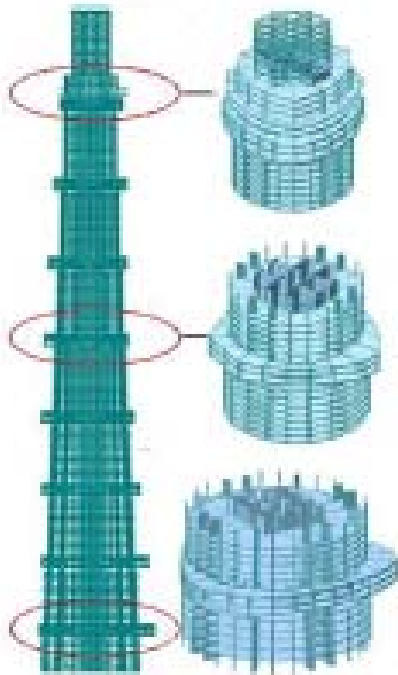
Shanghai Tower, China



Shanghai Tower (632 m), Canton Tower (600m), Shanghai World Financial Center (494 m), HK International Commerce Centre (484 m), Oriental Pearl (468m)

2. Case Studies of SHM of Civil Infrastructures in: China - monitoring of tall tower

Shanghai Tower, China



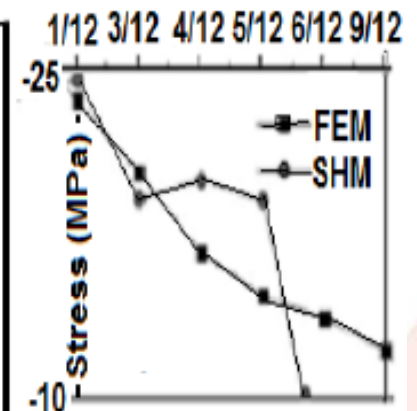
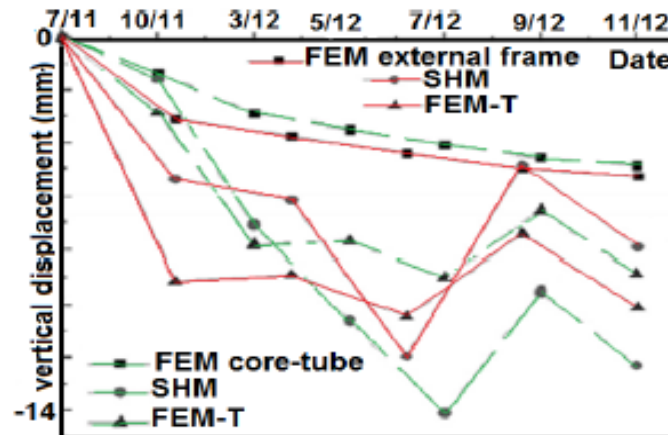
400 sensors of 11 types at 11 substations in 9 different zones: - 1m, 33.45m, 99m, 173.7m, 239.4m, 314.1m, 393.3m, 465.4m and 542m.



Strain sensors installed inside RC shear walls of the inner tube



Strain sensors installed on embedded steel column



- vertical deformation at representative locations on external frame and core-tube
- stress at fifth floor of a super column with and without temperature compensation

2. Case Studies of SHM of Civil Infrastructures in: India – post earthquake structures

Nepal Earthquake April-May 2015 - Tremors felt in India, China, Pakistan, etc.



How safe are the post earthquake structures?

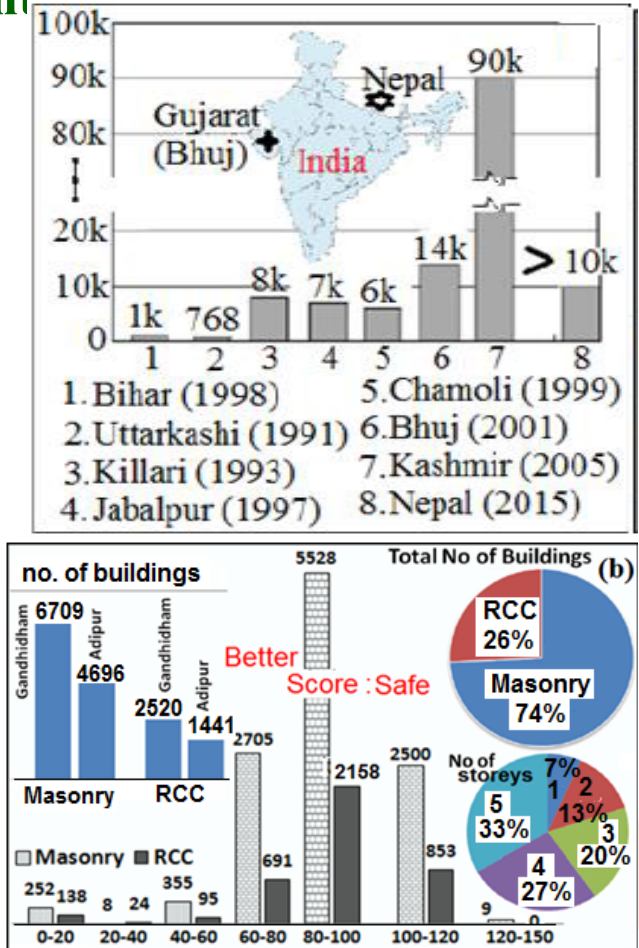
How safe are the partially destroyed structures?

How to instill confidence in the occupants of partially effected structures ?

2. Case Studies of SHM of Civil Infrastructures in: India – post earthquake structures

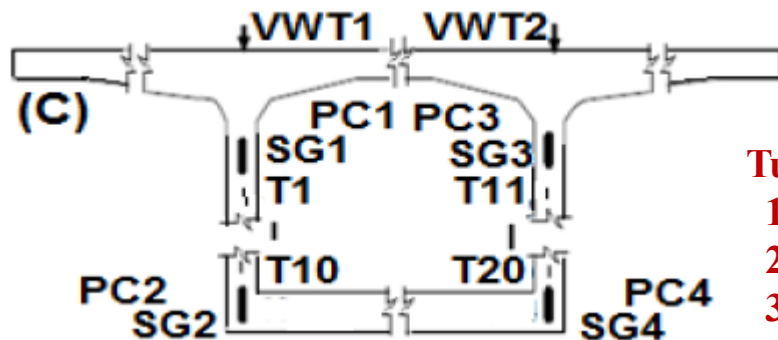
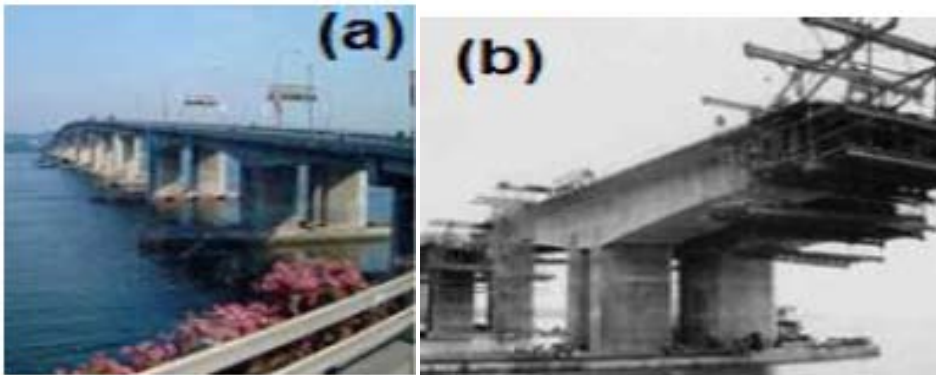
India: Post Earthquake Structural Safety Assessment

- Frequent earthquake in the Himalayan region has increased the demand for evaluating pre and post-earthquake structures.
- Even for meagre earthquakes, there were huge casualties due to non-compliance of building codes in these countries, coupled with non-enforcement by most of their governments.
- Pre and post-earthquake safety measures of human and structures are urgently needed in these countries. Recent earthquakes in Nepal reiterated this fact.
- Case Study: 50% of the Gujarat population was affected directly or indirectly by the Bhuj, Gujarat earthquake on 26 Jan 2001. A Rapid Visual Screening (RVS) was conducted on 16,000 buildings in the Gandhidham and Adipur cities.



2. Case Studies of SHM of Civil Infrastructures in: Singapore – link bridge with Malaysia

Tuas Second Link, Singapore



- Construction period: Oct 1994 - Oct 1997
- Overall length of bridge: 1,920 metres
- Length within Malaysian waters: 1,769 m
- Total length of piles: 10,230 m
- Total volume of concrete: 54,000 m³
- Total weight of reinforcing steel: 18,000 tons
- Total number of precast box segments: 840 units
- Longest span: 165 m

Tuas Second Link Bridge connecting Malaysia and Singapore.

- 1.Scenic view,
- 2.Bridge under construction, and
- 3.Arrangement of instruments in segment 31, which is closest to the pier. (PC, pressure cell; SG, strain gauge; T, thermocouple; VWT, temperature sensor.)
- 4.Monitoring was carried during construction

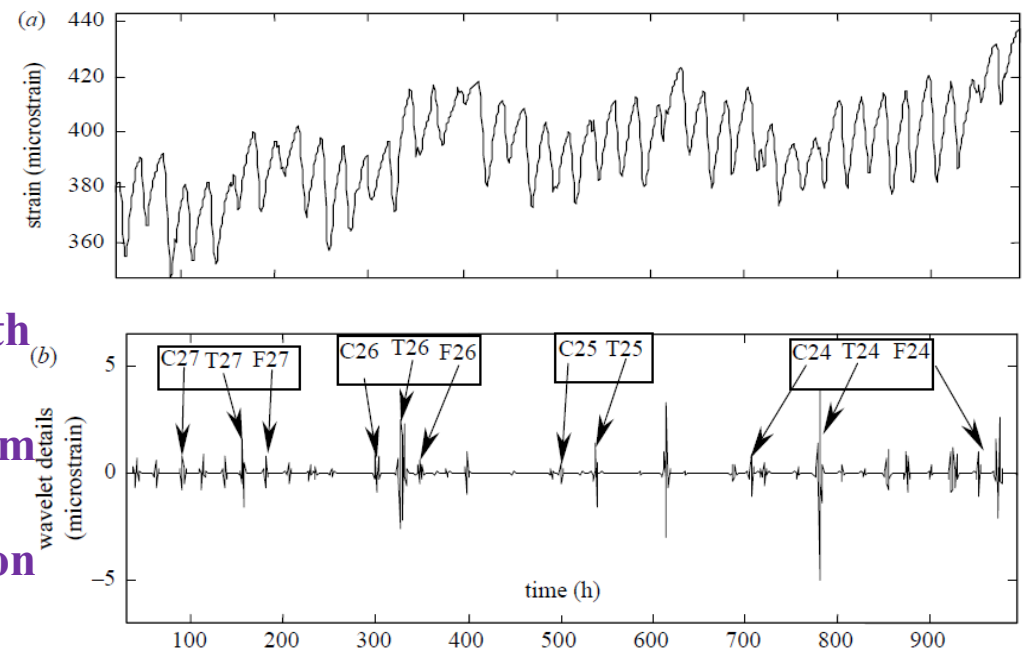


J. M. W. Brownjohn and P Moyo (2001). "Monitoring of Singapore-Malaysia second link during construction", *Proc. SPIE4317*, Second International Conference on Experimental Mechanics, 528 (June 13, 2001); doi:10.1117/12.429633; <http://dx.doi.org/10.1117/12.429633>

2. Case Studies of SHM of Civil Infrastructures in: Singapore – link bridge with Malaysia

Tuas Second Link, Singapore

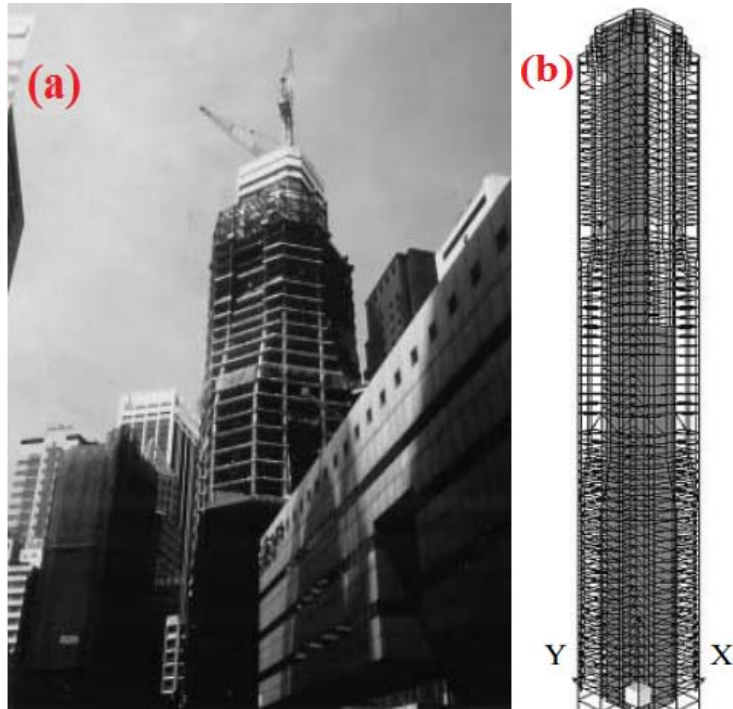
- Prestressed concrete box girder bridge carrying a dual carriageway with 3 lanes on each carriageway.
- 1.9km comprising 27 spans with cross-sections of the box girder varying in depth in each span.
- Singapore side of the bridge is about 170m and was cast in-situ using the balanced cantilever method to enable the navigation channel to be kept free throughout the construction.
- Box girder is monolithic with slender piers designed to accommodate longitudinal movement.



- (a) Strain data from segment 31 SG1, and
(b) Discrete wavelet transform level 1 details identifying discontinuities in strain time-series corresponding to construction events. C, concreting; T, cable tensioning; F, shifting of concreting form. e.g. T26, tensioning of cables in segment 26.

2. Case Studies of SHM of Civil Infrastructures in: Singapore – monitoring tall building

Republic Plaza, Singapore



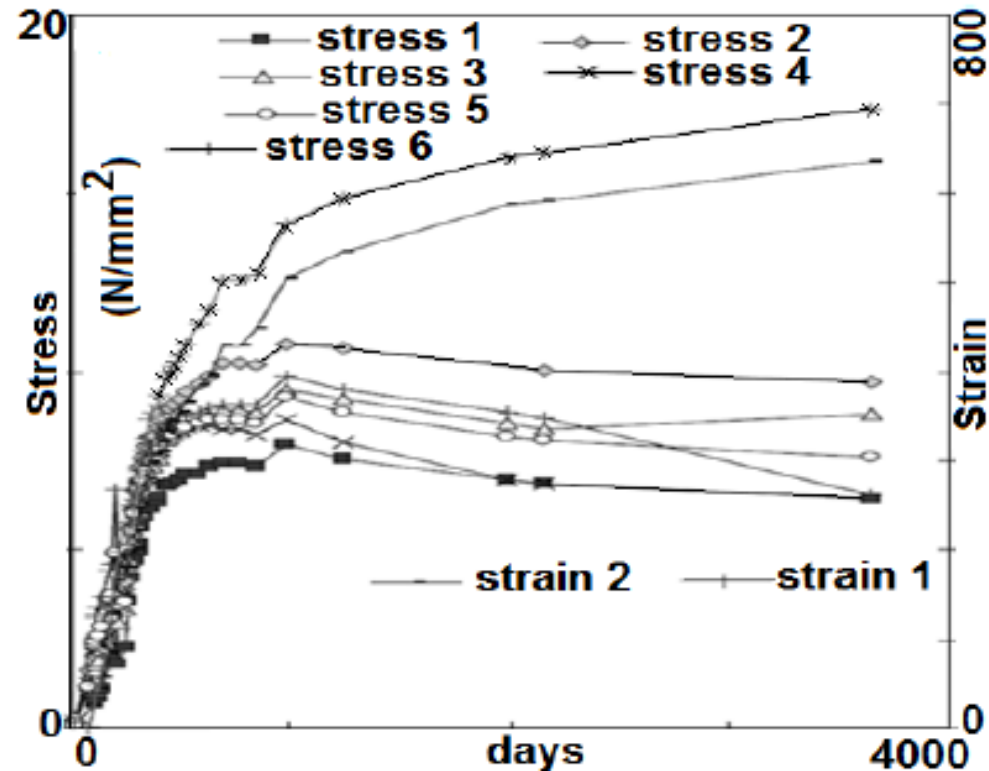
(a) Republic Plaza under construction,
(b) FE model showing structural elements

Brownjohn J. M. W. (2007) "Structural health monitoring of civil infrastructure", Phil. Trans. R. Soc. A (2007) 365, 589–622, doi:10.1098/rsta.2006.1925

1. A 65 storey, 280 m office tower in Singapore
2. Stress cells and SGs were installed in a representative 1/8th segment around the 18th level of the building.
 - Stress cells and SGs were installed in the concrete shear core and in the concrete within the steel columns.
 - SGs were installed on the main beams of the horizontal framing system of two floors and on the steel tubes of the external ring of vertical load-bearing columns
3. SGs were read manually at intervals during the construction and brief period following completion,
4. Fundamental translational frequencies were tracked by free vibration measurements during the latter part of the construction and beyond.
5. Revealed distribution of structural dead load and how the load distribution changed over time.

2. Case Studies of SHM of Civil Infrastructures in: Singapore – monitoring tall building

Republic Plaza, Singapore



- c) Republic Plaza after completion,
- d) Stresses (left) and strains (right) in the core wall before and after construction - using 2 SGs and 6 stress cells to show respective decrease and increase, indicating creep and load redistribution

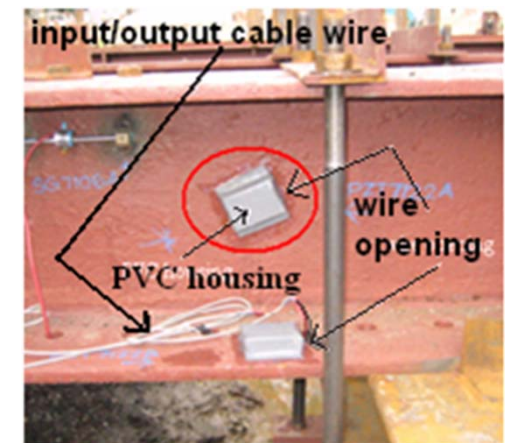
2. Case Studies of SHM of Civil Infrastructures in: Singapore – monitoring deep excavation

Telok Blangah MRT Station, Singapore

- CirCle Line (CCL) is an orbital line linking all radial lines leading to the city (33.3 km long with 29 stations).
- Telok Blangah is one of the underground stations
- Depth of excavation around 18 m, covering an area of approximately 4500 m²



Period of construction: 2006-2012



2. Case Studies of SHM of Civil Infrastructures in: Singapore – monitoring deep excavation

Telok Blangah MRT Station, Singapore

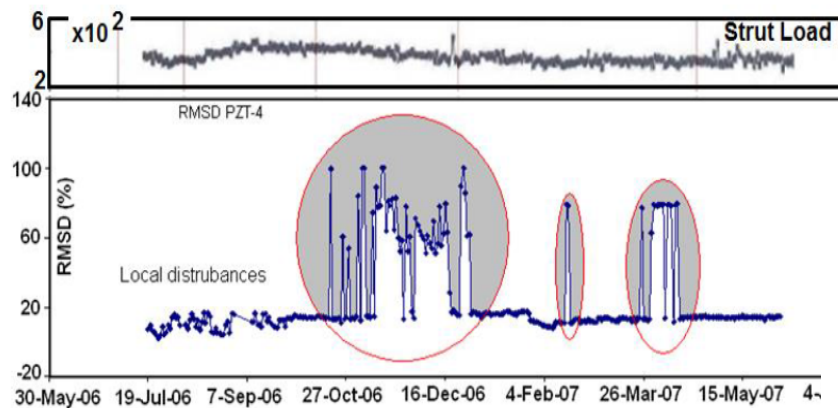


Deformation sensors (left), Profilometers (center), and Strain Gauges (right)

In total, at the three sites, installed with:

- 470 fiber-optic sensors
- 79 inclinometers,
- 212 strain gauges,
- 64 temperature sensors,
- 114 profilometers
- 21 deformation sensors and
- 60 PZTs

SHM included a web-based reporting and SMS alert system for real-time response



Large scale application of both PZT and FOS monitoring

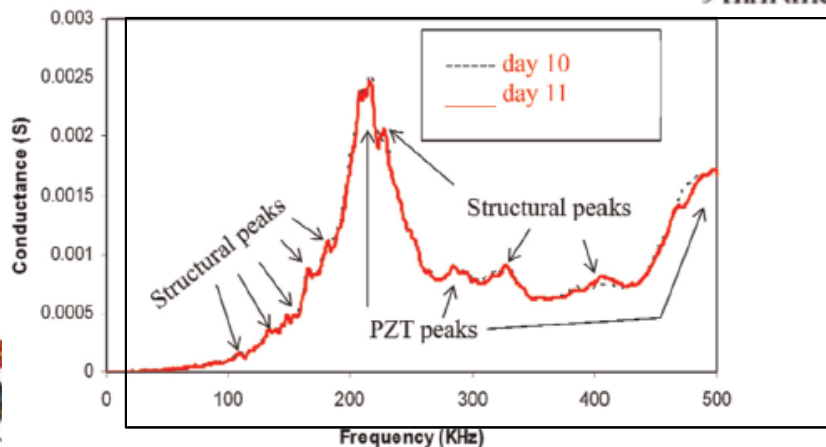
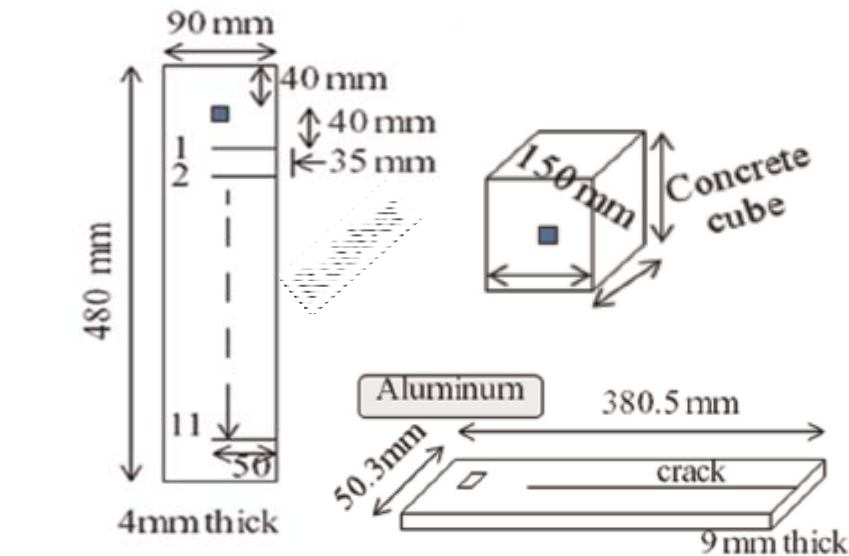
PZT based monitoring provided for monitoring of loads related to both local disturbances and global disturbances



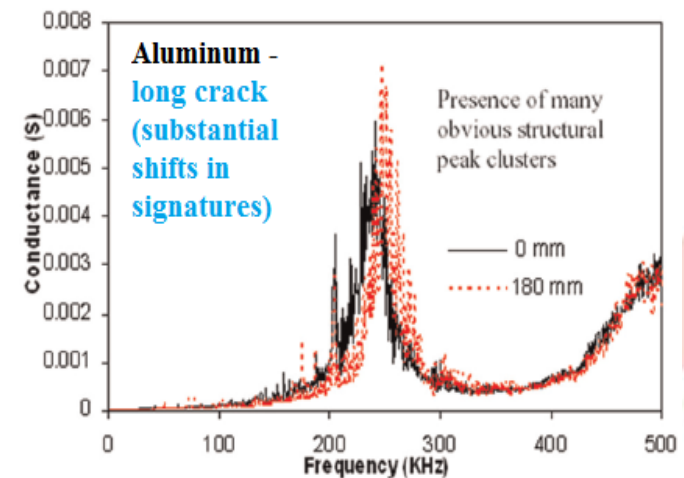
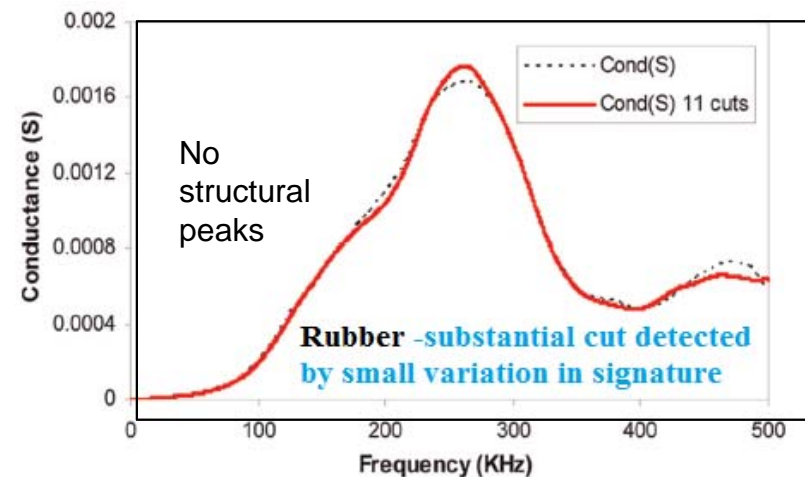
3. SHM Research at CEE, NTU - Health Monitoring

PZT based EMI and wave propagation techniques

- **Effective for initial damage detection**
- **More effective for metal than non-metal**

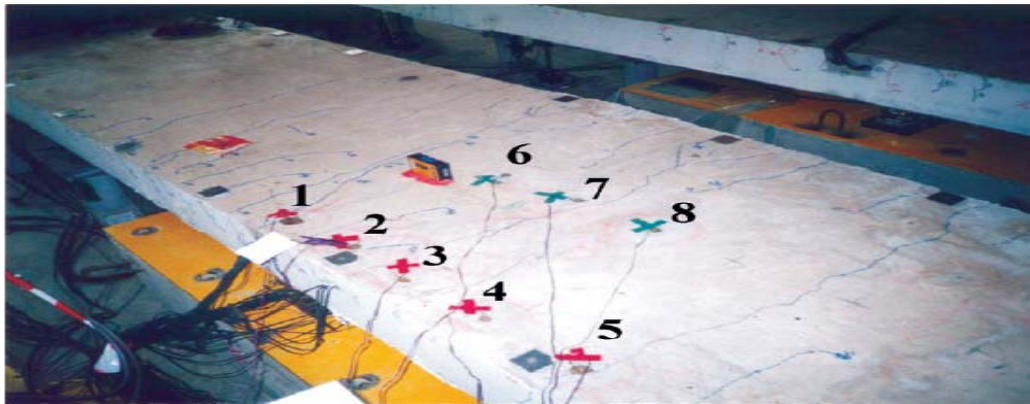


Concrete cube-curing on 10th-11th days



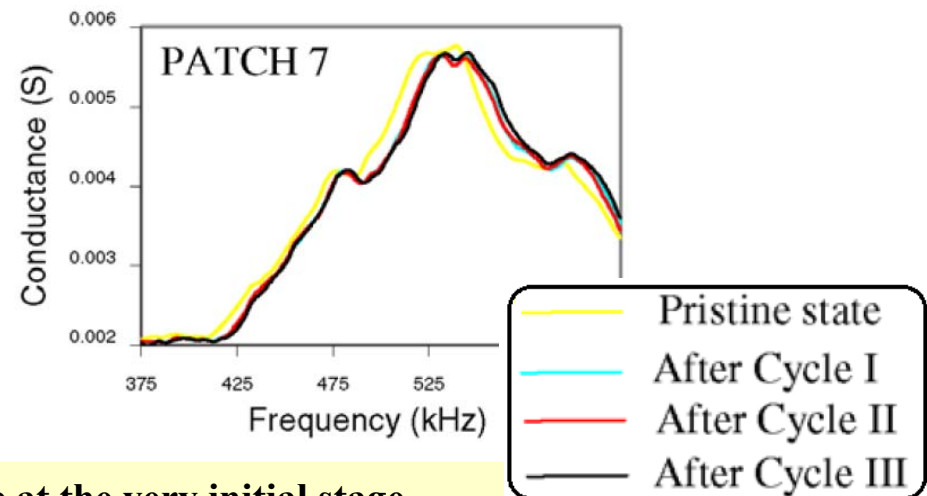
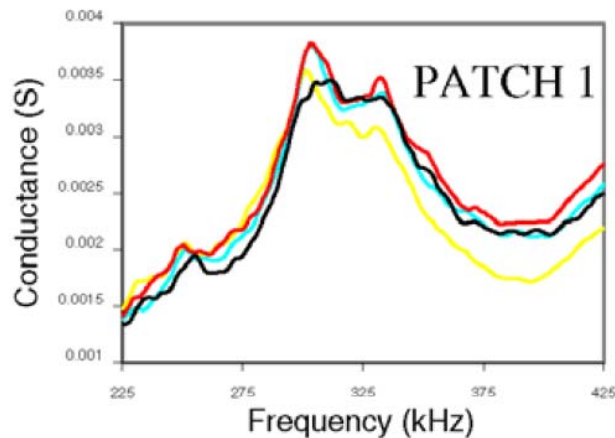
3. SHM Research at CEE, NTU - Health Monitoring

Destructive testing of a prototype RC bridge



Locations of PZTs)

- 10.35m long by 1m wide RC bridge, consisting of two 250mm deep longitudinal beams and supporting a deck slab of 100mm thick, was tested to destruction.
- 11 PZTs each of size 10mm by 10mm and 0.2mm thickness were used to monitor the test

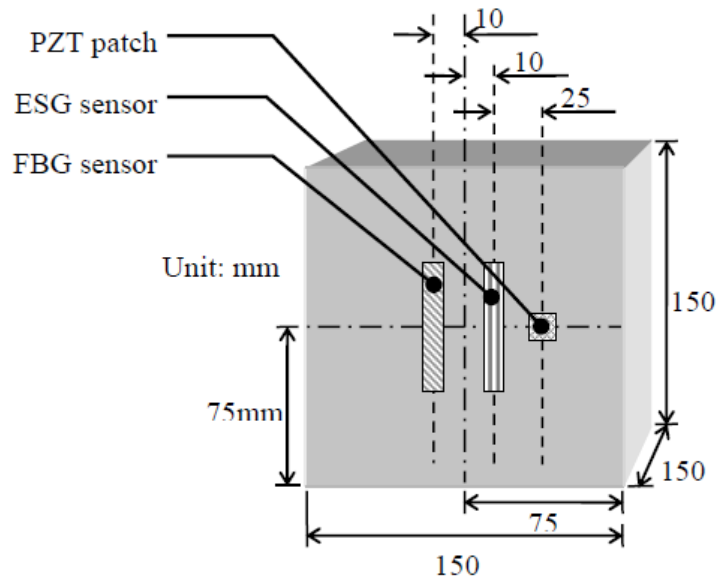


- demonstrated 'smartness' of PZT in detecting damage at the very initial stage.
- demonstrated feasibility of using PZT to monitor the health of large RC structures
- found that surface mounted PZT are very sensitive to the development of cracks in concrete, in their local vicinity.

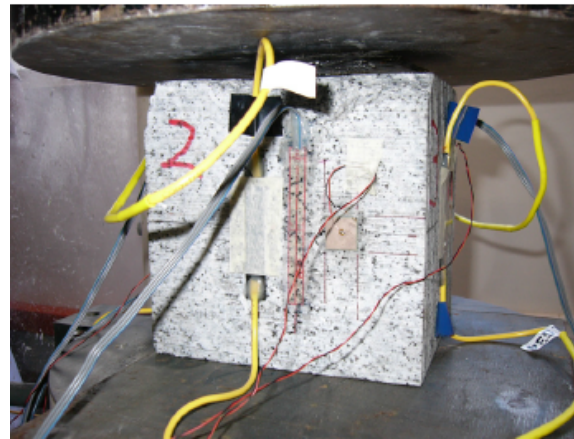
3. SHM Research at CEE, NTU - Health Monitoring

Monitoring of rocks using FBG, PZT and ESG sensors

(Sensors installed on four open faces)



PZT, FBG and ESG sensors



Loading Cycles

Load Cycle Number	Maximum Load (KN)	Strain measurement interval (KN)
1	500	100
2	1000	200
3	1500	300
4	2000	300
5	2500	300
6	2700	300
7	2900	300
8	2950	300

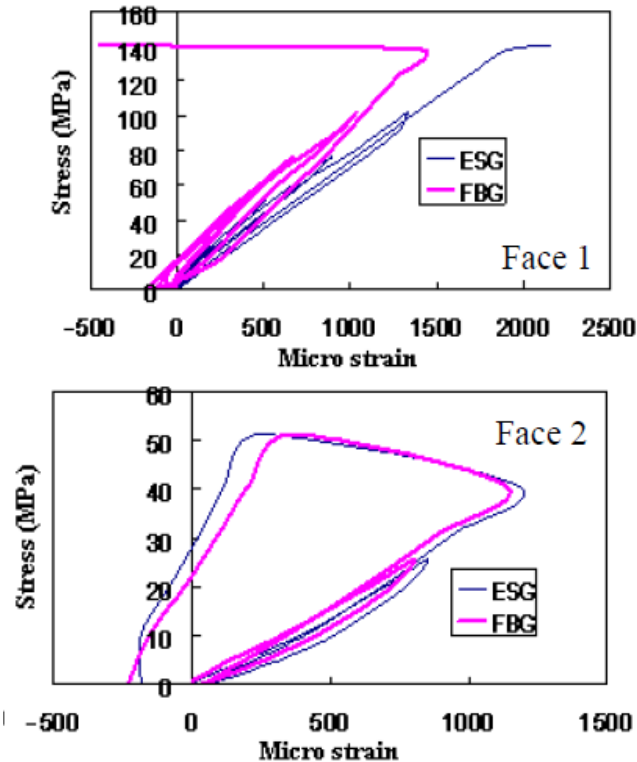
Destructive test of rock cube



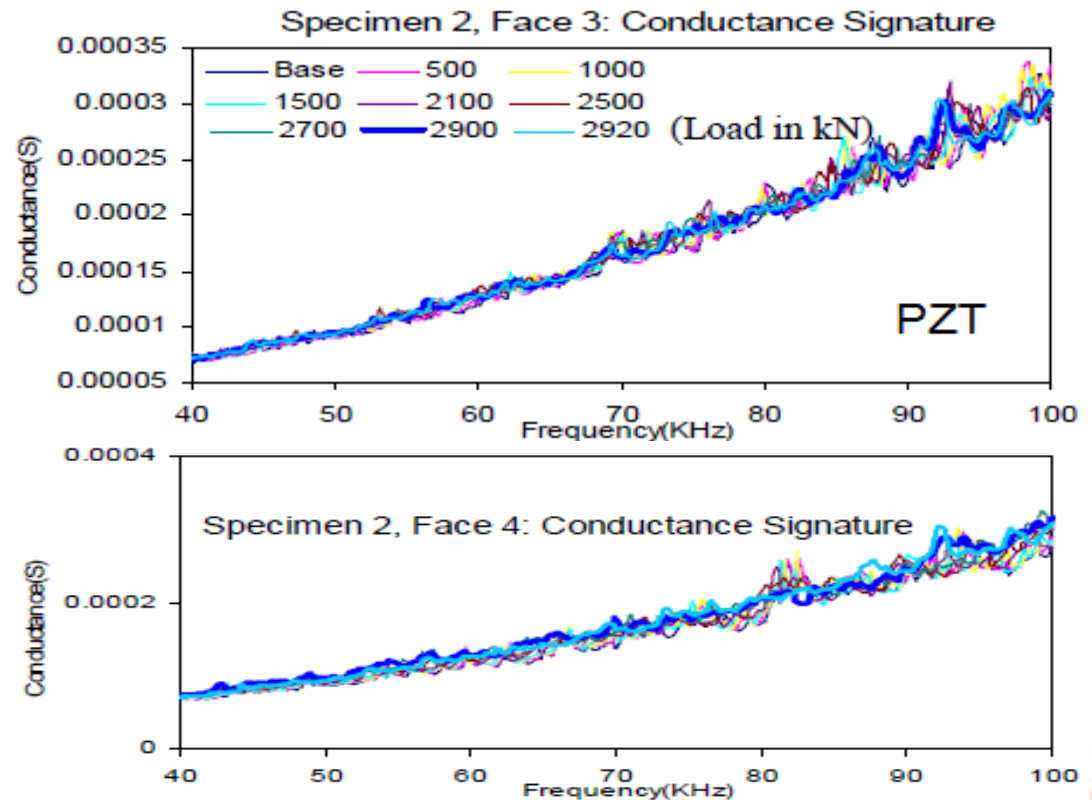
Specimen 2 after failure
(Face 1 being sheared off)

3. SHM Research at CEE, NTU - Health Monitoring

Monitoring of rocks using FBG, PZT and ESG sensors



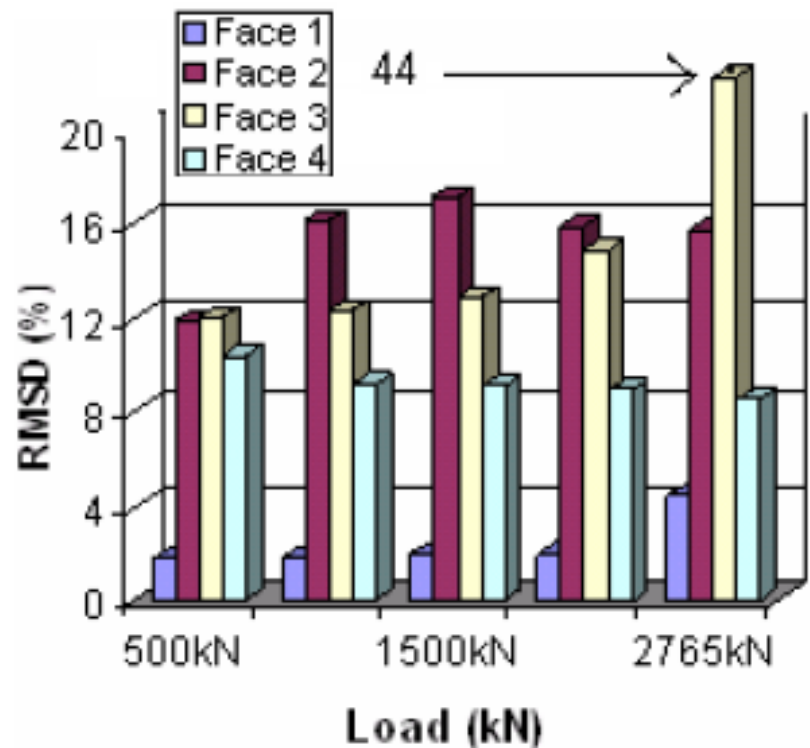
Comparison of stress-strain relationship measured by ESG and FBG sensors on Specimen 1 Faces 1 and 2.



PZT conductance signatures of Specimen 2 Faces 3 and 4.

3. SHM Research at CEE, NTU - Health Monitoring

Monitoring of rocks using FBG, PZT and ESG sensors



Specimen 1:

RMSD extracted from PZT signatures:

- Face 1 was the last to fail because its RMSD value is the smallest compared to Faces 2, 3 and 4.
- the order of failures should be Face 2 first, followed by Faces 3, 4 and 1

Conclusions from Experiments:

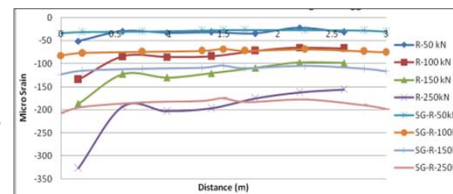
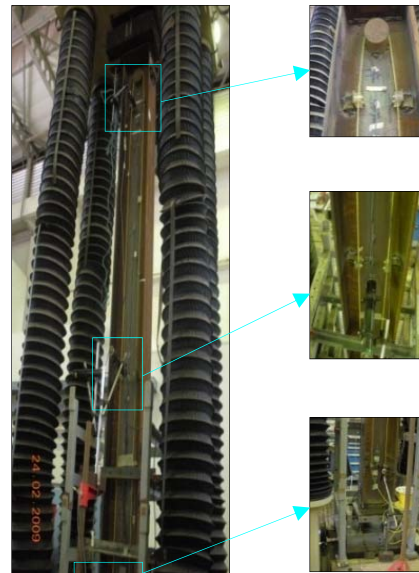
- ESG and FBG recorded strains on four faces but could not indicate the failure sequence.
- RMSD plots from PZT resulted conductance signatures indicated the sequence of failure of the four faces.
- Recommend ESG/ FBG for strain measurements and PZT for identifying sequence of failures.

3. SHM Research at CEE, NTU - Health Monitoring

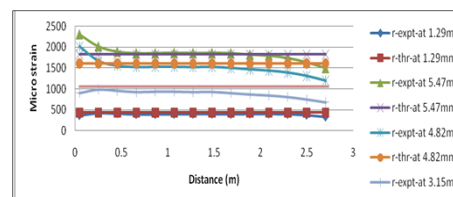
Fiber optic sensors for underground SHM

- A BOTDR (Brillouin Optical Time Domain Reflectometry) based SHM system that can survive drill-and-blast and shotcreting during construction.
- System can measure parameters (strain and temperature) at thousands of locations, along a single fiber sensor via distributed FOSs.
- Water spray test has been conducted in the laboratory to check the survivability of the sensors against shotcreting pressure.
- A trial test in an under-construction tunnel demonstrated that these customized sensors survived the pressure of shotcreting and drill-and-blast impact.
- Test readings were obtained weekly at the beginning, bi-weekly afterwards and monthly until end of construction. The deformation of the tunnel was estimated and compared with the total station measurements as the construction progresses .

A) Axial Load Test

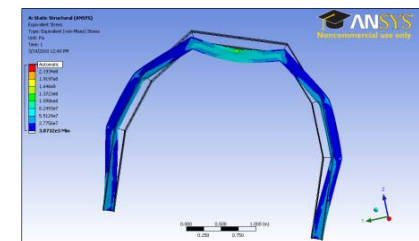
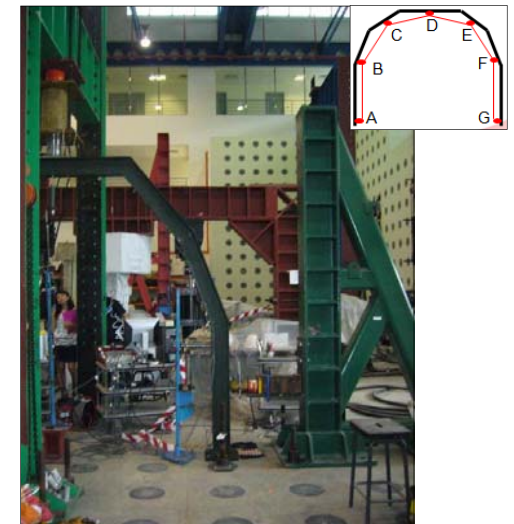


Compression Test results

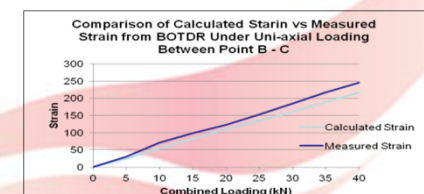


Tension Test results

B) Frame Test



Software Simulation of Frame

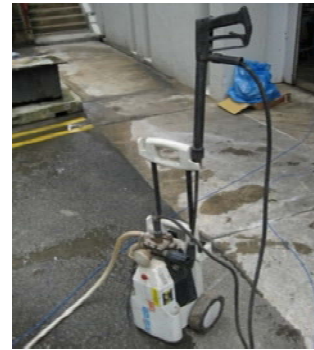


Frame Test results

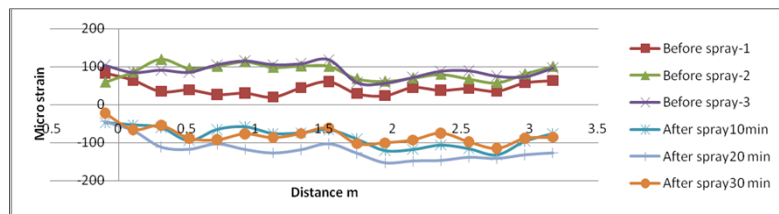
3. SHM Research at CEE, NTU - Health Monitoring

Fiber optic sensors for underground SHM

C) Water Spray Test



Water Spray Test Set up and Spray gun



Water Spray Test results on FOSs

Trial Test in JRC Tunnel (100m below)

Five sensors were installed to test their survivability against shotcreting, and drill-and- blast impact.



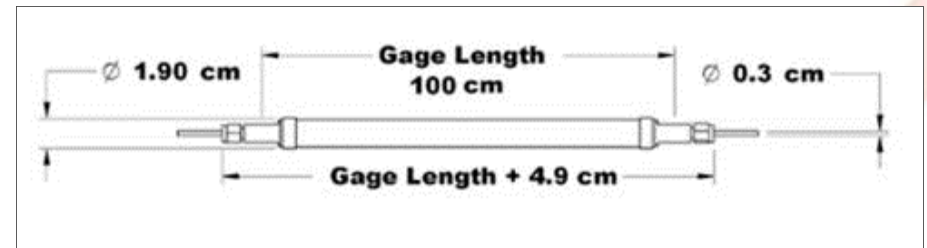
Sensor Installation : Before and after shotcreting in tunnel (AS3 Level1)



BOTDR sensor



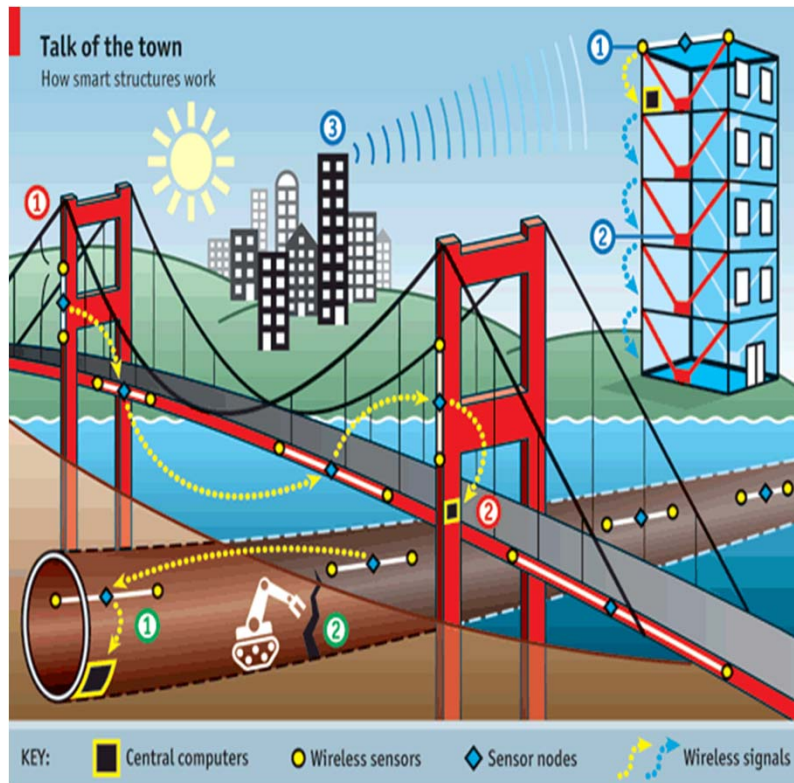
Flexible FBG sensor



Rigid FBG sensor

3. SHM Research at CEE, NTU - Energy Harvesting

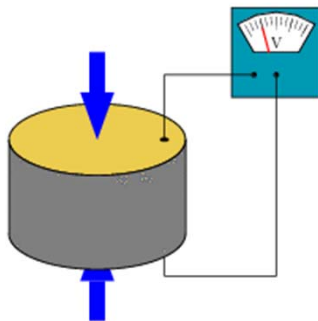
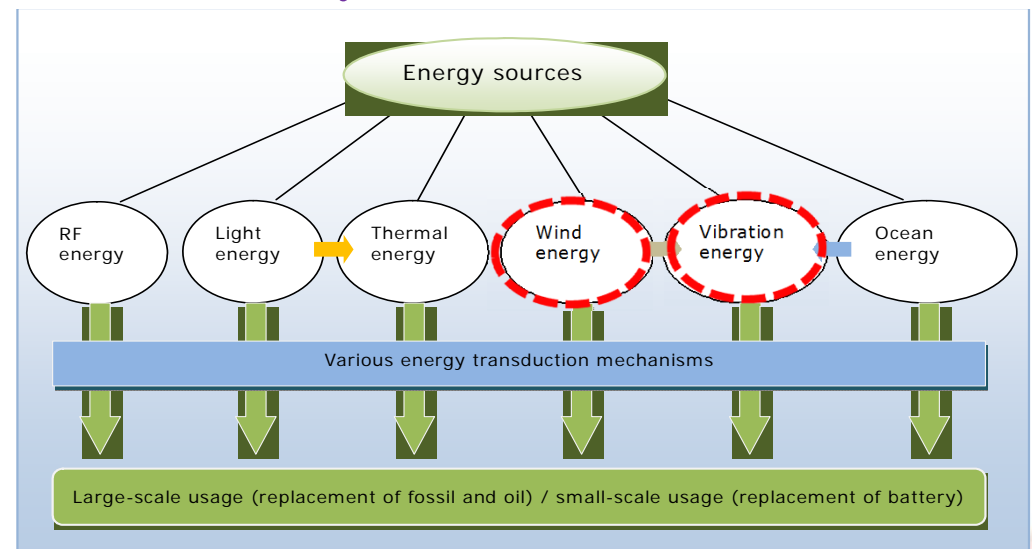
Self-powered wireless SHM



*Hurdle for Wireless Sensing Nodes (WSNs): **Power***

Harvest energy from the environment

- *self-powered
- *maintenance-free
- *eco-friendly



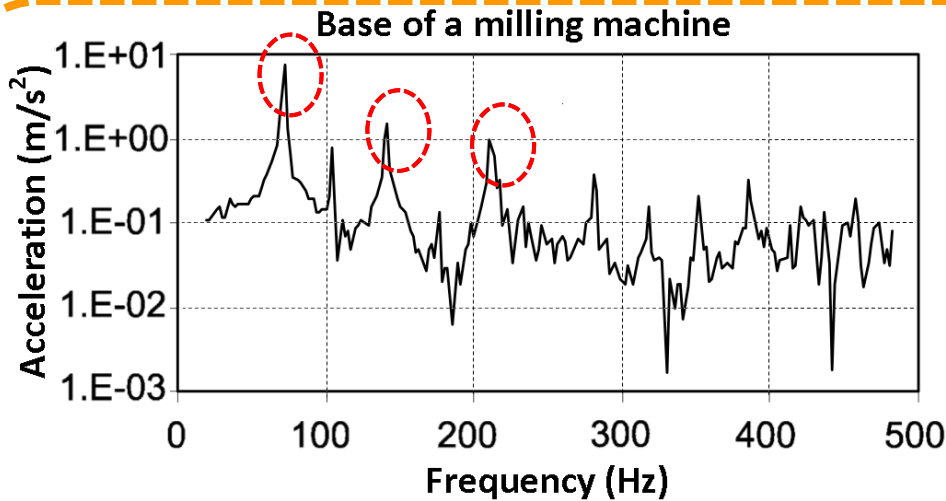
Advantages of Piezoelectric energy harvesting

- ease of implementation and integration (MEMS)
- high voltage level => no voltage transformation
- high power density

3. SHM Research at CEE, NTU - Energy Harvesting

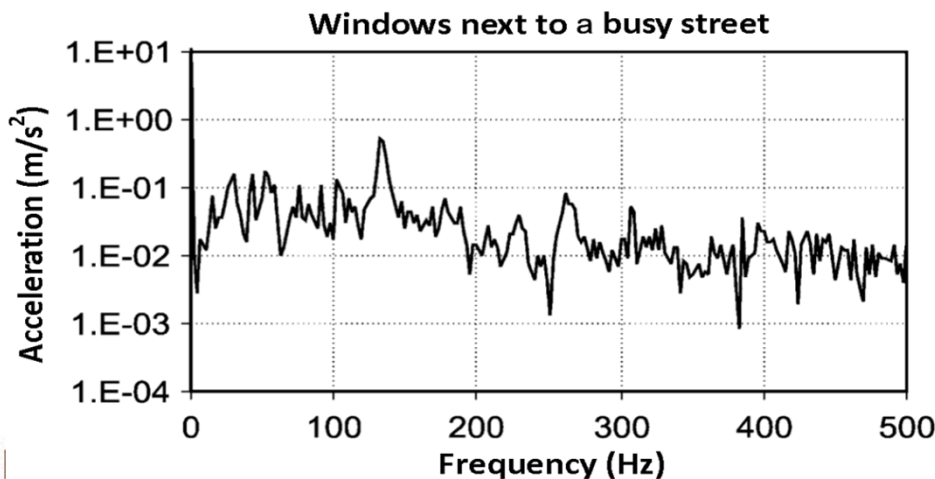
Vibration Powered Energy Harvester

Practical Vibration Sources



Multiple primary frequencies
e.g. Machinery in various operating modes

Peaks clustered (not separated far away)
e.g., 75Hz, 140Hz, 210Hz



Relatively uniform distribution in low
frequency range \Rightarrow not suitable

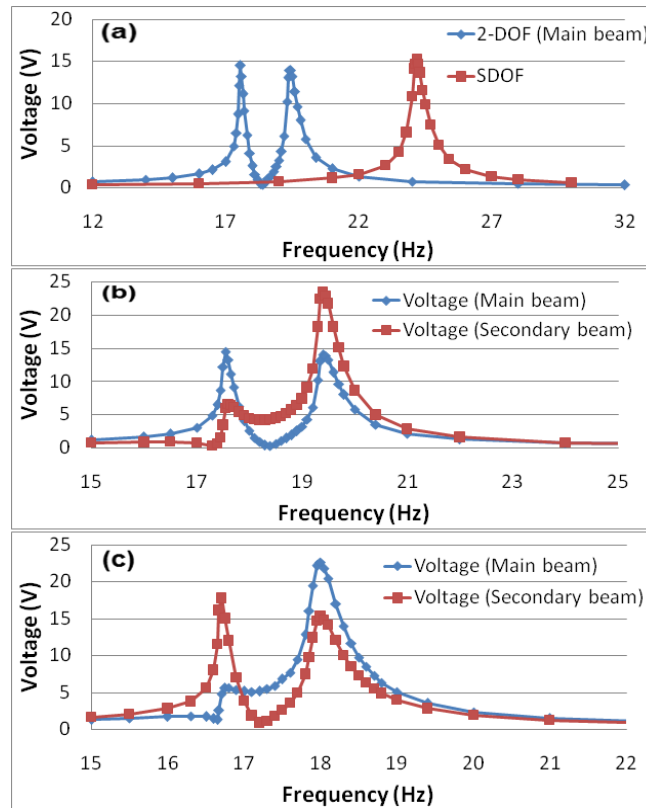
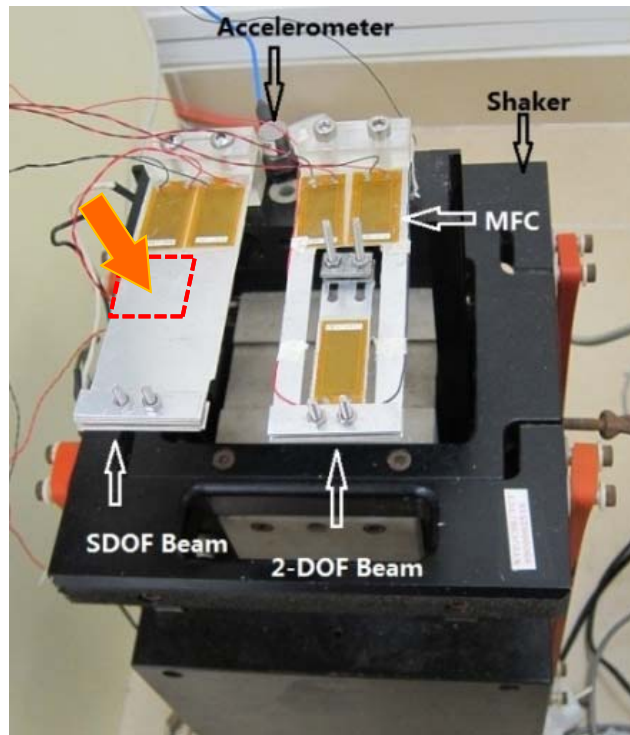
We studied two configurations to
demonstrate the feasibility of vibration
powered energy harvesters (VPEH)

1. Cut-out 2DOF Beam Configuration
2. 2DOF Nonlinear VPEH (with magnets)

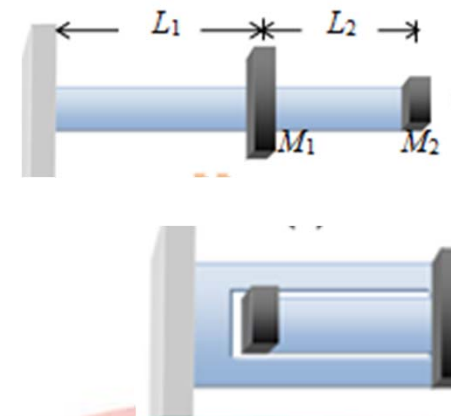
3. SHM Research at CEE, NTU - Energy Harvesting

Vibration Powered Energy Harvester

1. Cut-out Beam 2DOF Configuration – Experiment



- ✓ Two close peaks achieved
- ✓ Both significant amplitude
- ✓ Use cantilever efficiently (inner beam also used)
- ✓ More compact

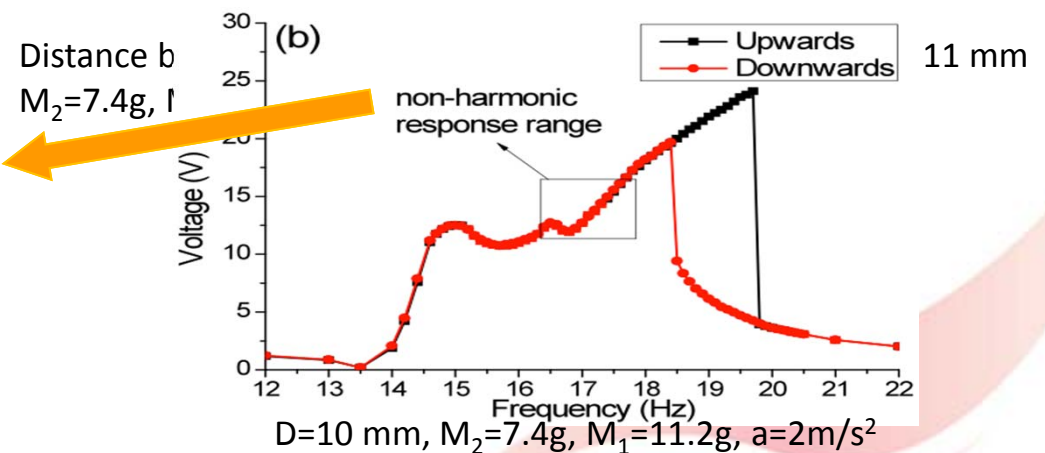
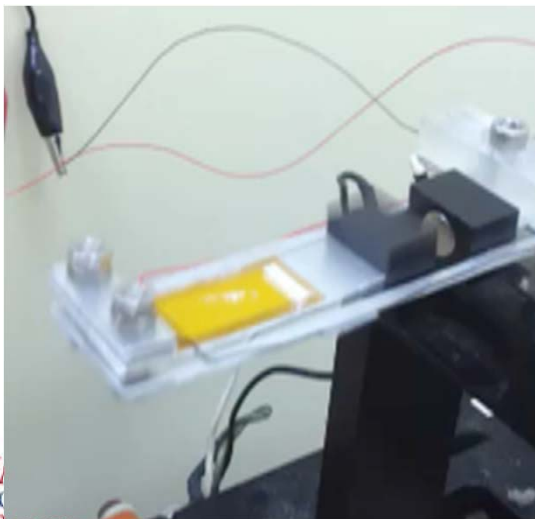
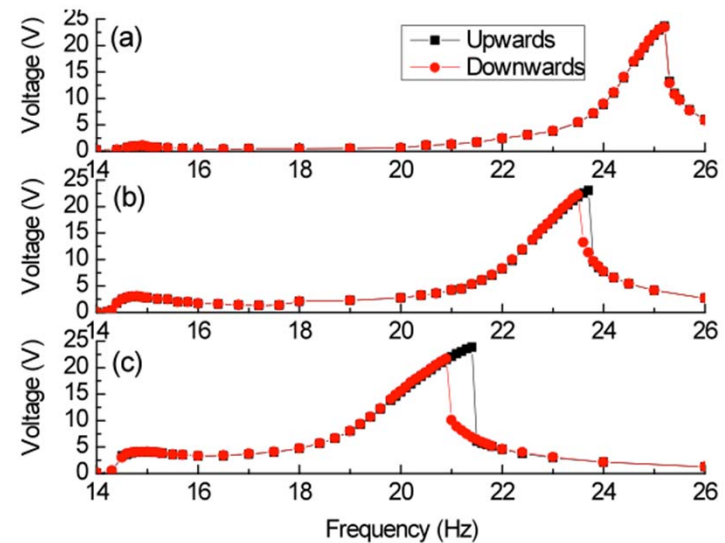
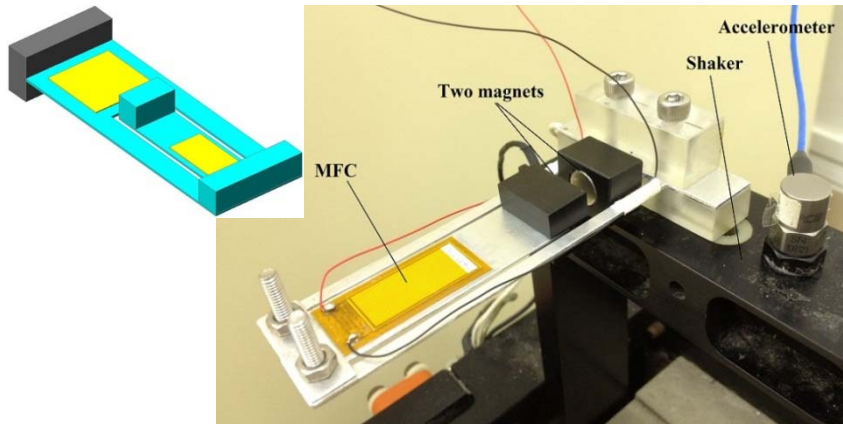


- (a) 2DOF Main beam ($M_1=7.2\text{g}$, $M_2=11.2\text{g}$) vs SDOF ($M_3=7.2\text{g}$)
- (b) Main and secondary beams of 2-DOF ($M_1=7.2\text{g}$, $M_2=11.2\text{g}$)
- (c) Main and secondary beams of 2-DOF ($M_1=7.2\text{g}$, $M_2=14.2\text{g}$)

3. SHM Research at CEE, NTU - Energy Harvesting

Vibration Powered Energy Harvester

2. 2DOF Nonlinear VPEH (by adding magnets) – Experiment



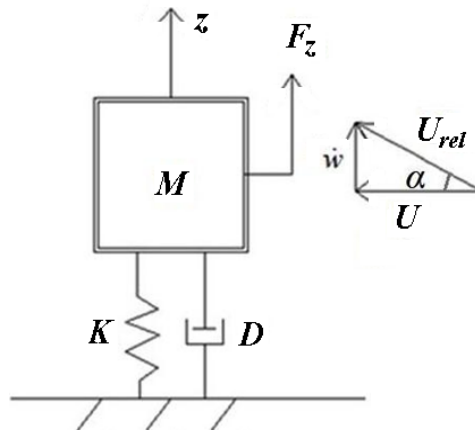
3. SHM Research at CEE, NTU - Energy Harvesting

Wind Powered Energy Harvester

Non-conventional wind energy harvesting
– exploiting aerodynamic instabilities

Gallop

- flutter
- Buffeting
- Wake galloping
- Vortex-induced vibration



- ✓ large vibration amplitude
- ✓ able to oscillate in infinite wind speed range

Gallop Principle

$$M\ddot{w}(t) + D\dot{w}(t) + Kw(t) = F_z(t)$$

$$F_z(t) = \frac{1}{2} \rho_a S U^2 C_{F_z} \quad C_{F_z} = \sum_{i=1,2,\dots} A_i(\alpha)^i \quad \alpha = \frac{\dot{w}(t)}{U}$$

$$M\ddot{w}(t) + \left\{ D - \frac{1}{2} \rho_a S U \left[\sum_{i=1,2,\dots} A_i \left(\frac{\dot{w}(t)}{U} \right)^{i-1} \right] \right\} \dot{w}(t) + Kw(t) = 0$$

$$D - \frac{1}{2} \rho_a S U A_1 \quad \text{linear}$$

$$-\frac{1}{2} \rho_a S U \left[\sum_{i=2,\dots} A_i \left(\frac{\dot{w}(t)}{U} \right)^{i-1} \right] \quad \text{nonlinear}$$

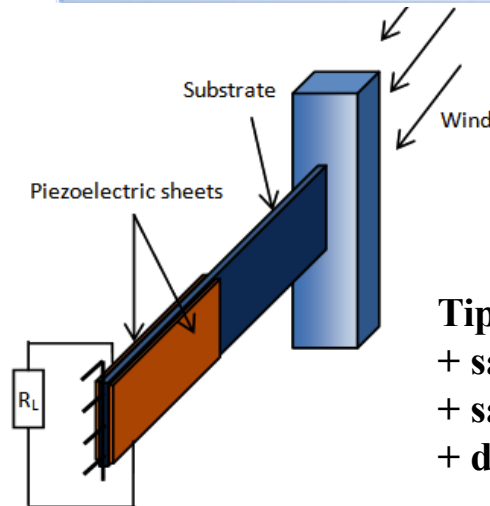
- ✓ Stable limit cycle oscillation
- ✓ “self excited” & self-limiting

3. SHM Research at CEE, NTU - Energy Harvesting

Wind Powered Energy Harvester






Galloping Piezoelectric Energy Harvester (GPEH)

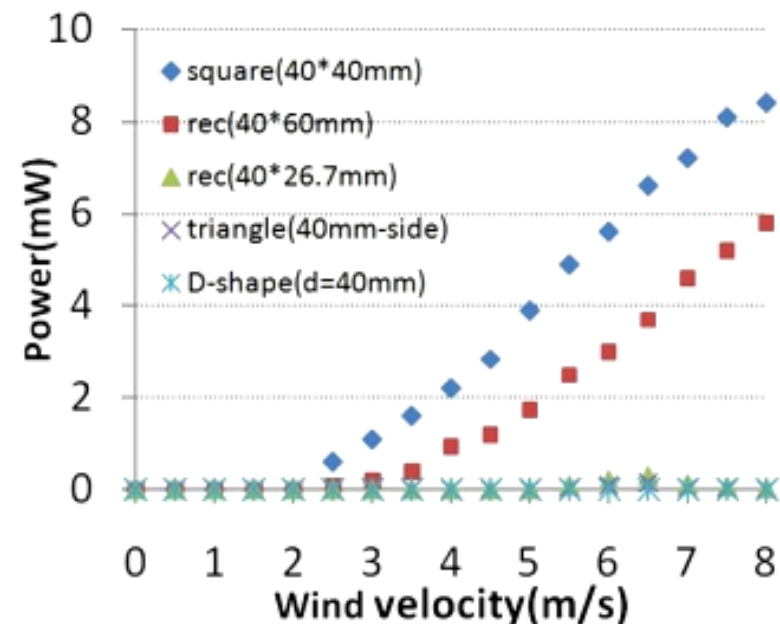
– Experimental Comparative Study



Tip body:

- + same weight
- + same windward area
- + different cross sections

Section shape					
dimension h×d (mm)	40×40	40×60	40×26.7	40 (side)	40 (dia.)

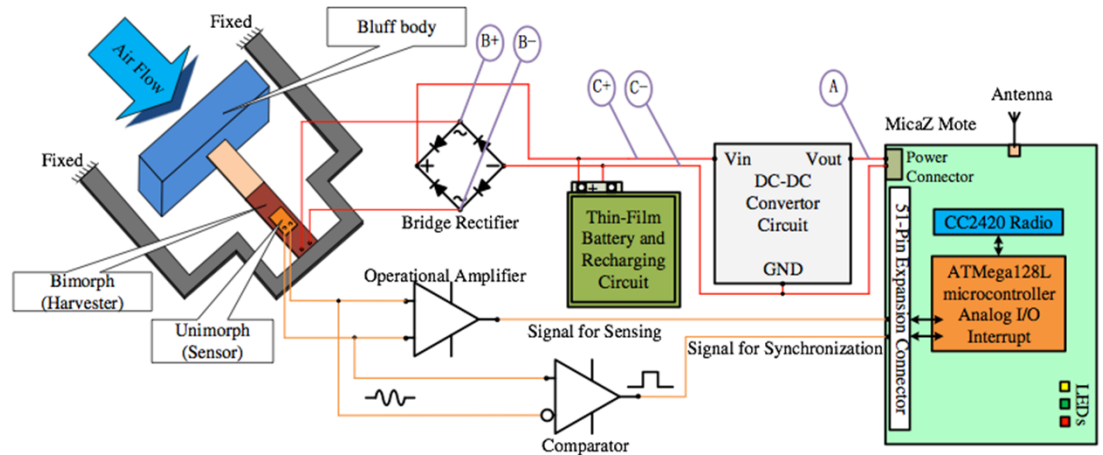
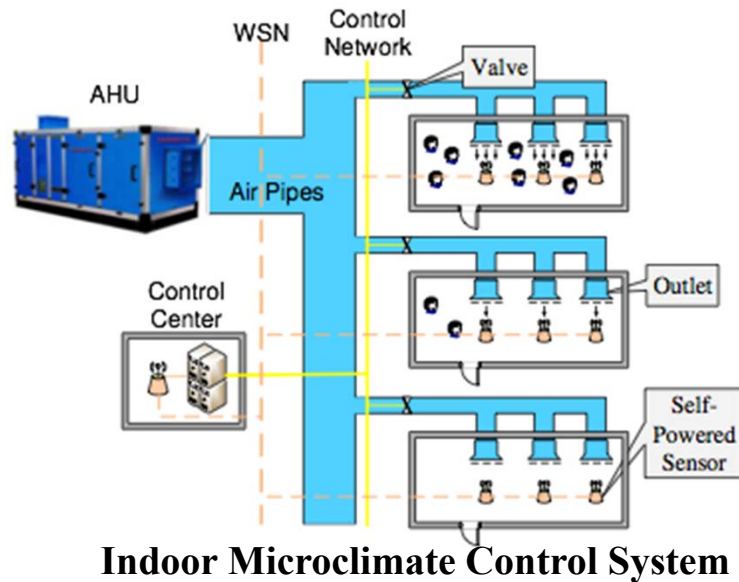


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Yang YW, Zhao LY and Tang LH (2013), “Comparative study of tip cross-sections for efficient galloping energy harvesting”, *Applied Physics Letters*, 102(6), 064105.

3. SHM Research at CEE, NTU - Energy Harvesting

Wind Powered Energy Harvester – an application



Trinity (wireless sensors): Energy harvesting, Synchronous Duty-Cycling & Sensing

~3m/s



NANVANG

Xiang TY, Chi ZC, Li F, Luo J, Tang LH, Zhao LY and Yang YW (2013), "Powering indoor sensing with airflows: a trinity of energy harvesting, synchronous duty-cycling, and sensing", *11th ACM Conference on Embedded Networked Sensor Systems (SenSys 2013)*, Rome, Italy, 11-15 November.

4. Summary

- Proper SHM of civil infrastructures can save lives and properties.
- SHM of civil infrastructures is crucial especially when it involves modifications to existing/ neighboring structure, fatigue, long-term movement or degradation of materials, and accidental loads or natural calamities like earthquake.
- SHM is also important to provide feedback to improve future design based on performance-based design philosophy or when novel construction methods are used.
- Application of SHM technology in Asia is expected to grow rapidly in pace with its economic growth



Thank You!

