Invited Lecture at University of Seoul on November 10, 2016

Smart Structure Technologies for Safe and Resilient Urban Infrastructure

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Contents

Introduction

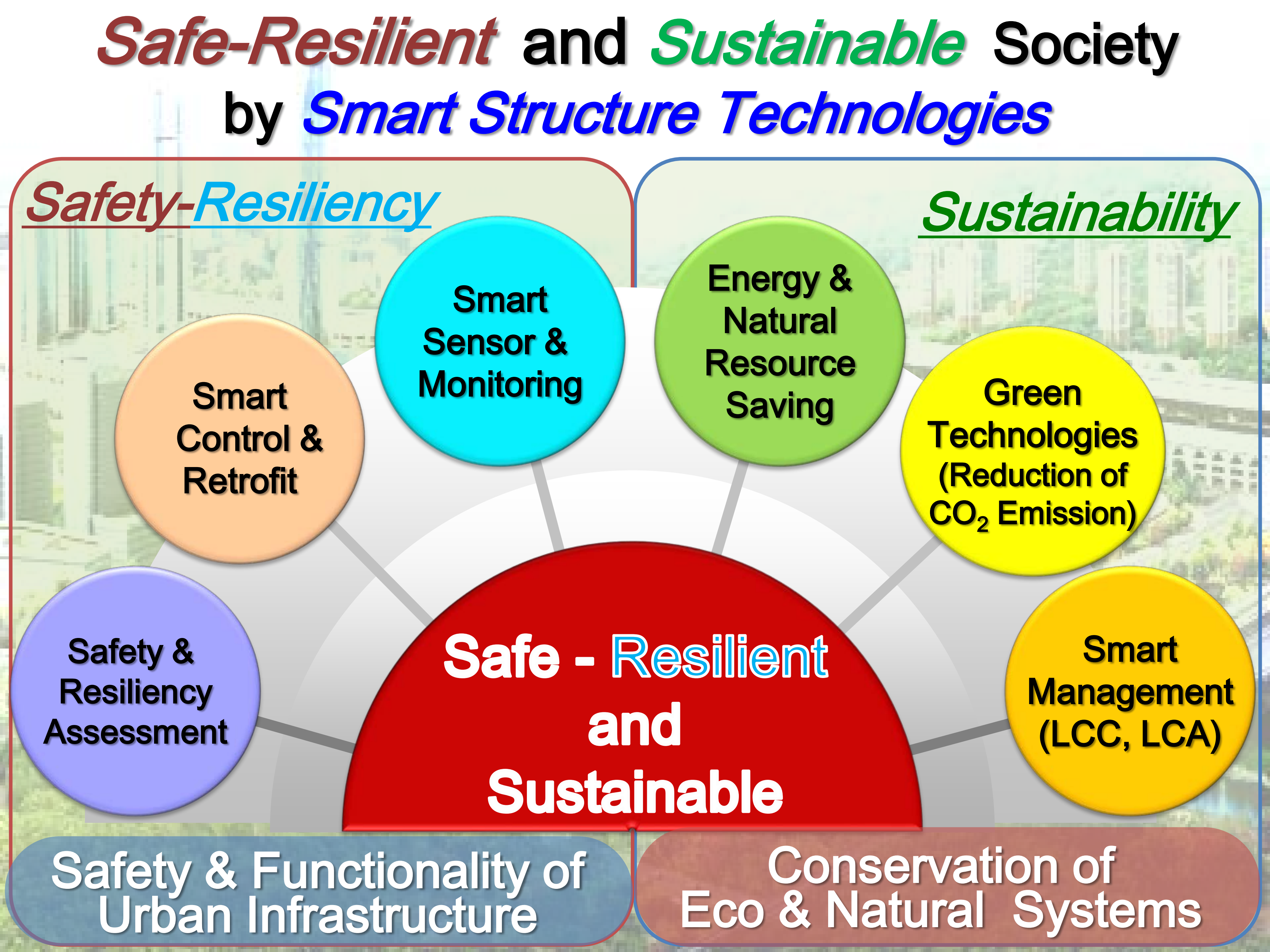





Smart Urban Infra-structure Technologies

Key Technologies of Smart Urban Infra-structure

Sensing	- Smart Sensors: Optical, Wireless, Piezo-electric, .. - Structural Health Monitoring - Data Communication: Wireless / Internet
Diagnosis	- On-board Processing for On-line Diagnosis - Signal Processing & Pattern Recognition - Condition Assessment
Actuation	- Structural Control - Smart Materials/Devices/Systems - Smart Retrofit & Maintenance
Management	- Safe, Secure, & Resilient Infra-structure - Eco-friendly & Sustainable Infra-structure - Life-cycle Cost & Asset Management


Safe-Resilient and Sustainable Society
by Smart Structure Technologies
Safety-Resiliency
Sustainability
Safety & Resiliency Assessment
Smart Control & Retrofit
Smart Sensor & Monitoring
Energy & Natural Resource Saving
Green Technologies (Reduction of CO_2 Emission)
Smart Management (LCC, LCA)
Safe - Resilient and Sustainable
Safety & Functionality of Urban Infrastructure
Conservation of Eco & Natural Systems

Super-tall Buildings

Empire State Bldg.
USA (449m, 1932)

Burj Khalifa Tower
UAE (828m, 2010)

Taipei 101 Tower
Taiwan (509m, 2003)

Shanghai Tower
China (632m, 2014)

Lotte World Tower
Korea (555m, 2016)

Height of Super Tall Buildings ⇨ 1 km.

Super-long Span Bridges

Golden Gate Bridge (1937), USA
Main Span - 1280m

Akashi Bridge (1998), Japan
Main Span - 1991m

Yisoonshin Bridge (2012), Korea
Main Span - 1545 m

Sutong Bridge (2008), China
Main Span - 1088 m

Russky Bridge (2012), Russia
Main Span - 1104m

Incheon Bridge (2009), Korea
Main Span - 800 m

Main Span Length of Super-long Bridge ⇨ 3 km.

Historical Structures

Parthenon
Greece (5th C. BC)

Tower of Pisa
Italy, (14th C.)

Sophia Cathedral
Turkey (5-15th C.)

Great Walls
China (2th C. BC)

Bulkuksa
Korea (6th C.)

Taj Mahal
India (17th C.)

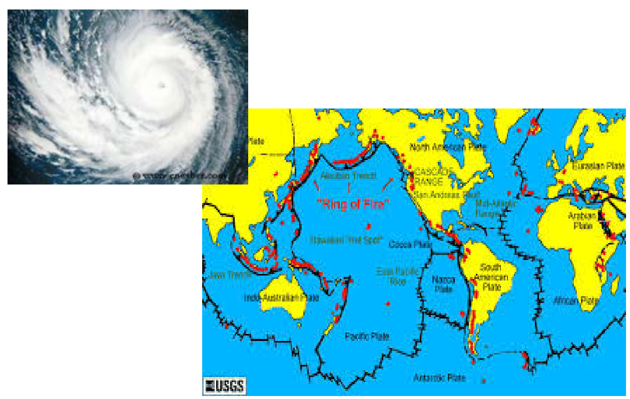
Natural Disasters

Earthquake in San Francisco (M=6.9, 1989)
Casualty: 63, Damage: $6Billion

Earthquake in Kobe (M=6.8, 1995)
Casualty: 6,434, Damage: $200Billion

Tsunami & LOCA at Fukushima (2011)
Casualty: over 27,000

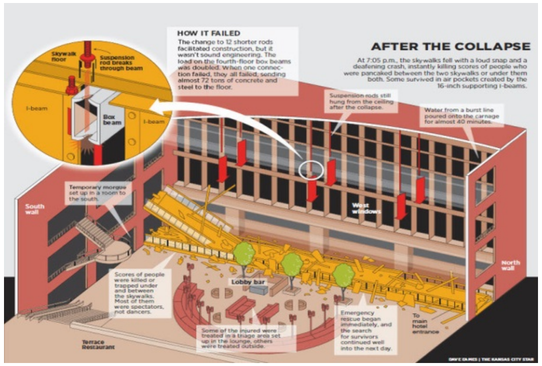
Hurricane Katrina (2005)
Casualty: 2,541, Loss: $100Billion



Global Warming & Earthquake

Typhoon Maemi in Korea (2003)
Casualty: 135, Loss: $5Billion

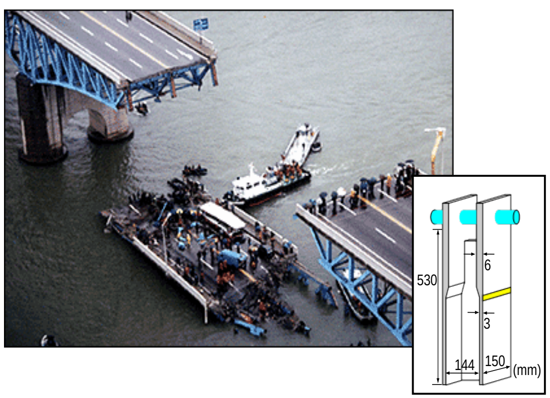
Man-caused Disasters



Hyatt Regency Hotel (1981)
Casualty: 114 , Injured: 216

Department Store (1995)
Casualty: 502, Injured: 937.

World Trade Center (2001)
Casualty: 2,997, Injured: 6,000.



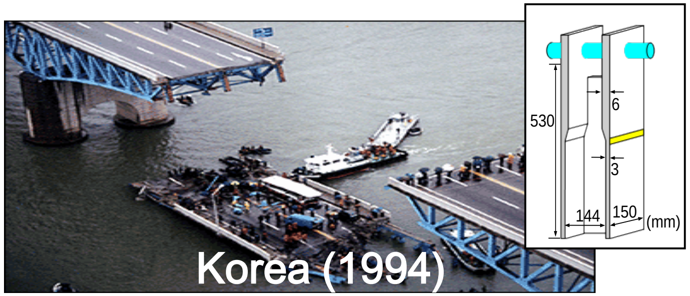
Sungsu Bridge (1995)
Casualty: 36.

ICE High-speed Trains (1998)
Casualty: 101, Injured: 88.

Collapse during Construction (2002)
Casualty: 1, Injured: 7

Aging Civil Infrastructure

- Collapses of Infrastructure



Korea (1994)


US (2007)


France (2004)

- Aging Infrastructure in the US:

12.1% structurally deficient and
14.8% functionally obsolete (ASCE).

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

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

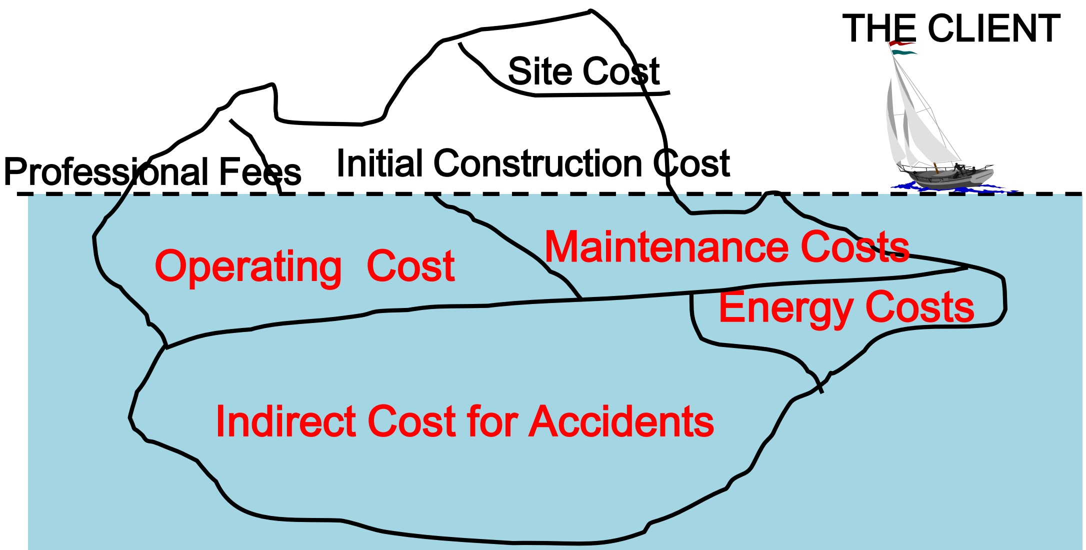
A = Exceptional
B = Good
C = Mediocre
D = Poor
F = Failing

Continuous Maintenance Operations are Needed:
Monitoring, Diagnosis, Repair, Retrofit, Prognosis, etc

(Courtesy of JS Kong at Korea U.)

Prediction of Life-Cycle Performance

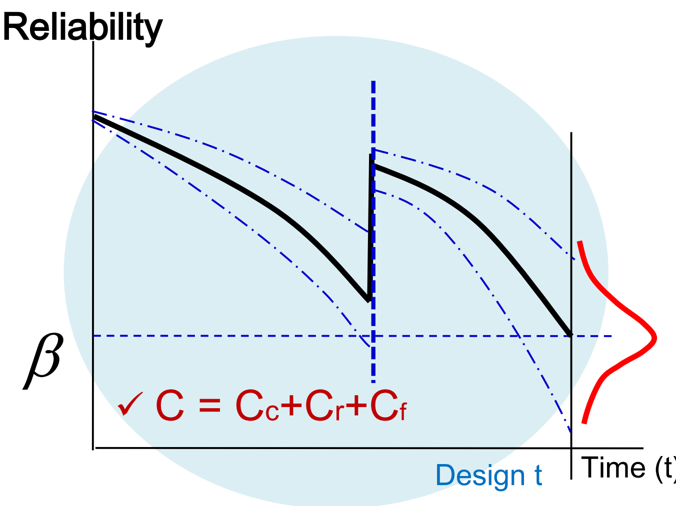
Total Life Cycle Cost (LCC)



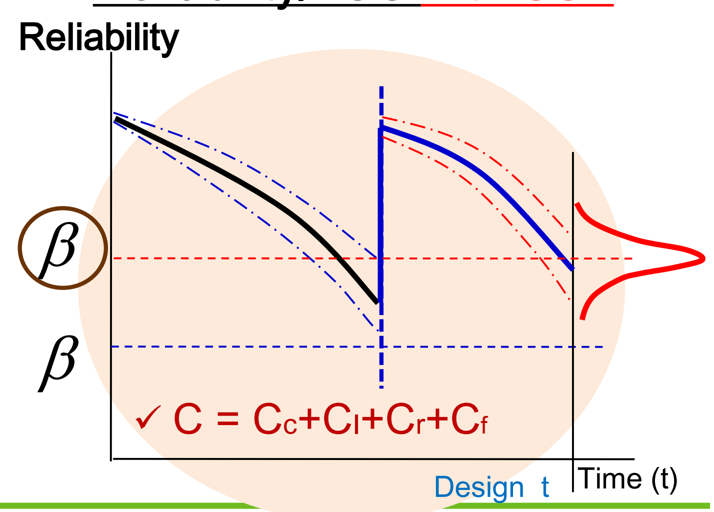
Life Cycle Assessment (LCA) for CO_2E

- Considering environmental impact, particularly on CO2 emission during the life of infrastructure systems.

Reliability /LCC without SST



Reliability/LCC with SST



Resiliency of Urban Infrastructural Systems

Definition of Resiliency:

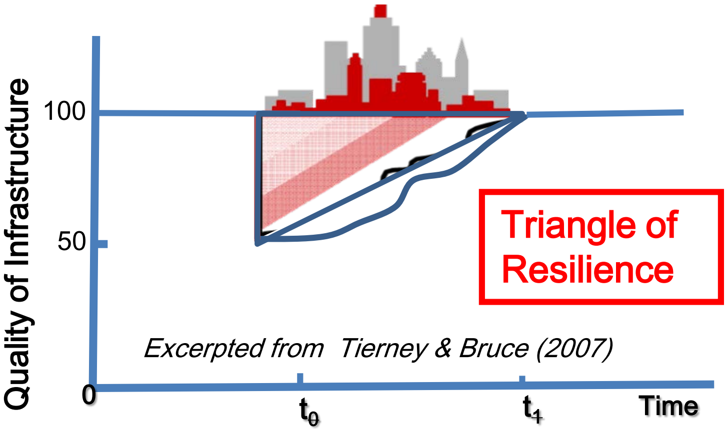
The ability of a system or society exposed to hazards to resist, absorb, accommodate to, and recover from the effects of the hazard in a timely and efficient manner through the preservation and restoration of its essential structures and functions. (UNISDR)

- Recovery after Unthinkable Disasters : Blank Swan
(Above Design Level : e.g. LOCA).

Measures for Resiliency;

Down Time for Business Restoration,

Economic Loss, Environmental Impact, etc.



Smart Sensors and Structural Health Monitoring





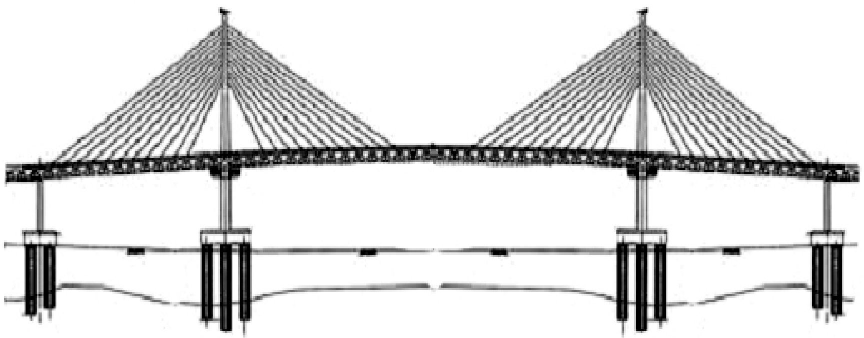

Monitoring System of Seo-Hae Bridge in Korea

Purpose of Structural Health Monitoring *(BF Spencer, UIUC)*

- To validate the structural designs and characterize performance
- To monitor and control the construction process
- To update current FE model for safety assessment in the future
- To detect and localize damage before reaching a critical level
- To assist maintenance/retrofit operation
- To assist emergency response efforts, including traffic control

(Courtesy of Y. Fujino, U. of Tokyo)

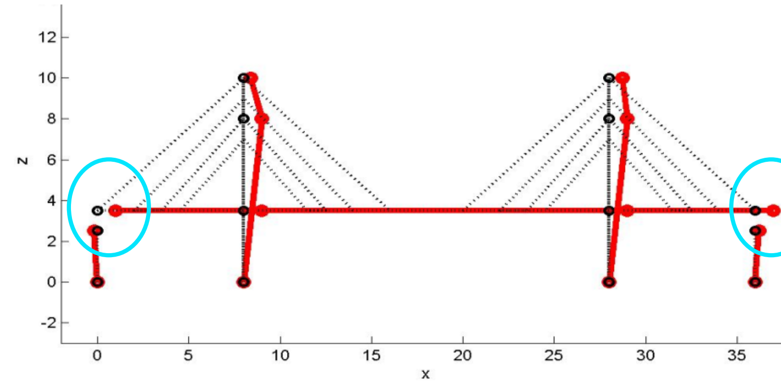
Monitoring of Yokohama Bay Bridge in Japan



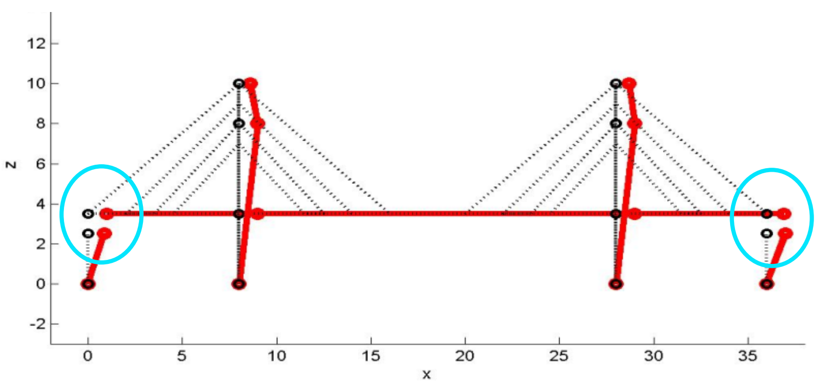
80 sensors

measured for 20 years

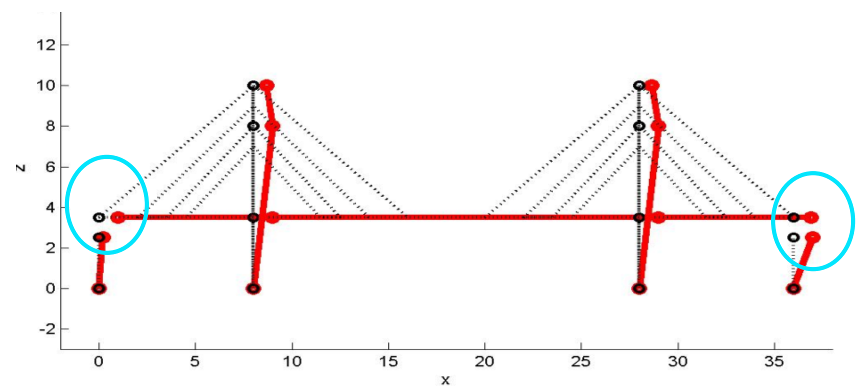
with more than 10 earthquakes passed



(a) Identified **Slip-Slip** Modes
(Earthquake 1990-02-20)
Assumed in Design



(b) Identified **Stick-Stick** Modes
(Earthquake 1992-02-02)

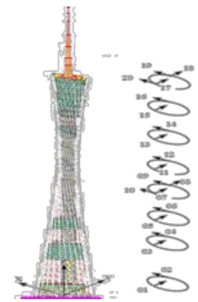


(c) Identified Mixed **Slip-Stick** Modes
(Earthquake 1995-07-03)

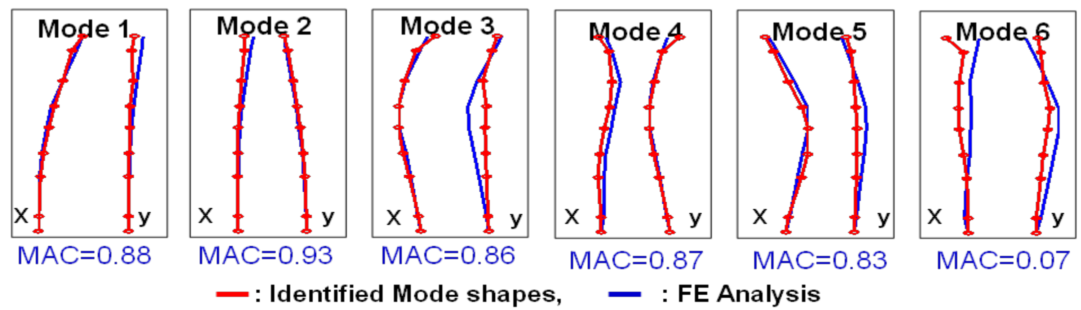
A Benchmark Problem for SHM of a TV Tower

Canton New TV Tower

http://www.cse.polyu.edu.hk/benchmark/index.htm



Identified Modal Properties from Vibration Data



1) to provide an *open platform to the researchers and practitioners* in the field of SHM and exchange their innovative strategies, and

2) to *apply various algorithms to the real high-rise slender structures* and examine the reliability of the techniques

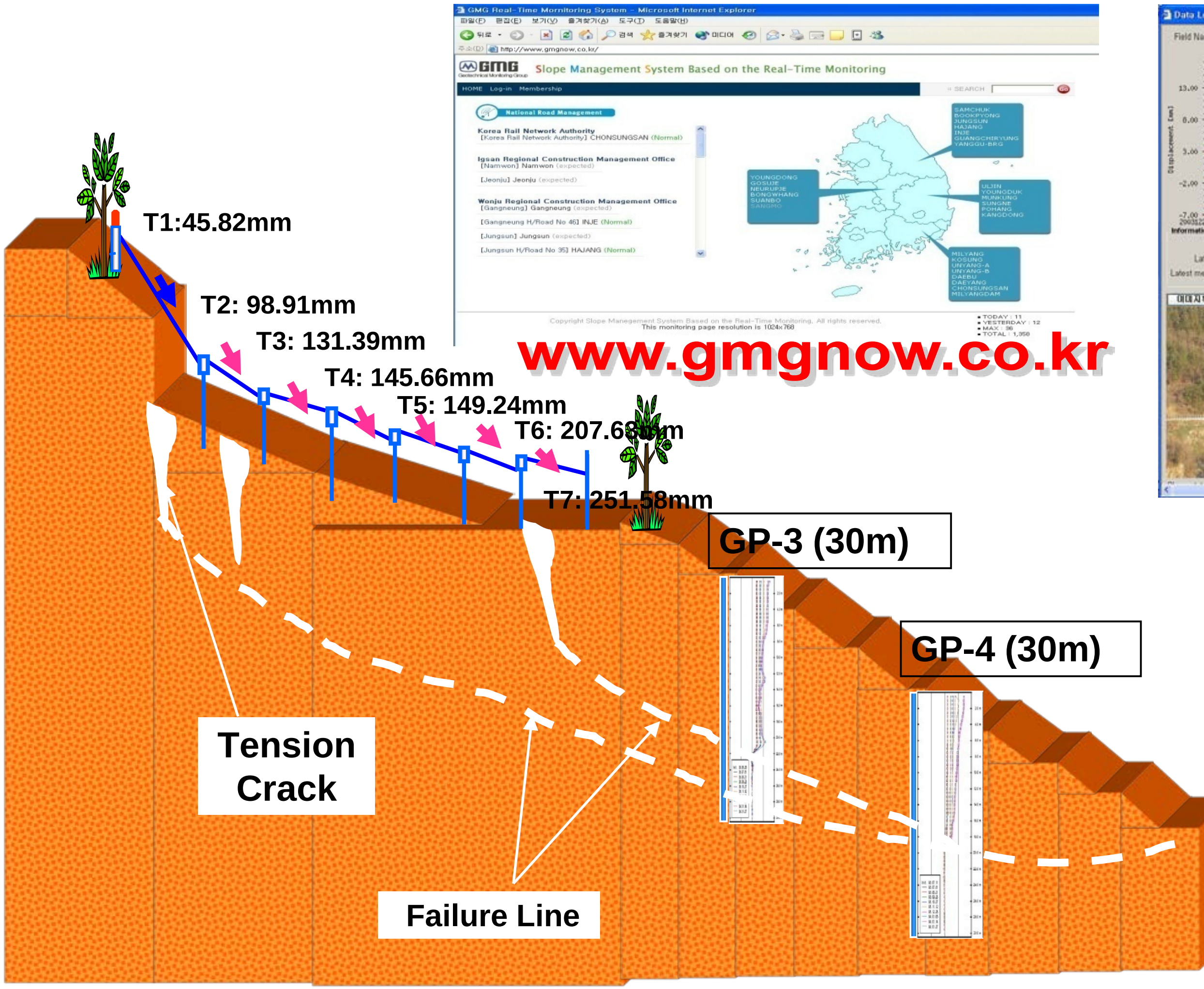
(Courtesy of K-T. Chang, Kumoh Inst. Tech.)

Internet-based Slope Monitoring System

Internet-based Warning System

www.gmgnow.co.kr

Real-time Warning Signal

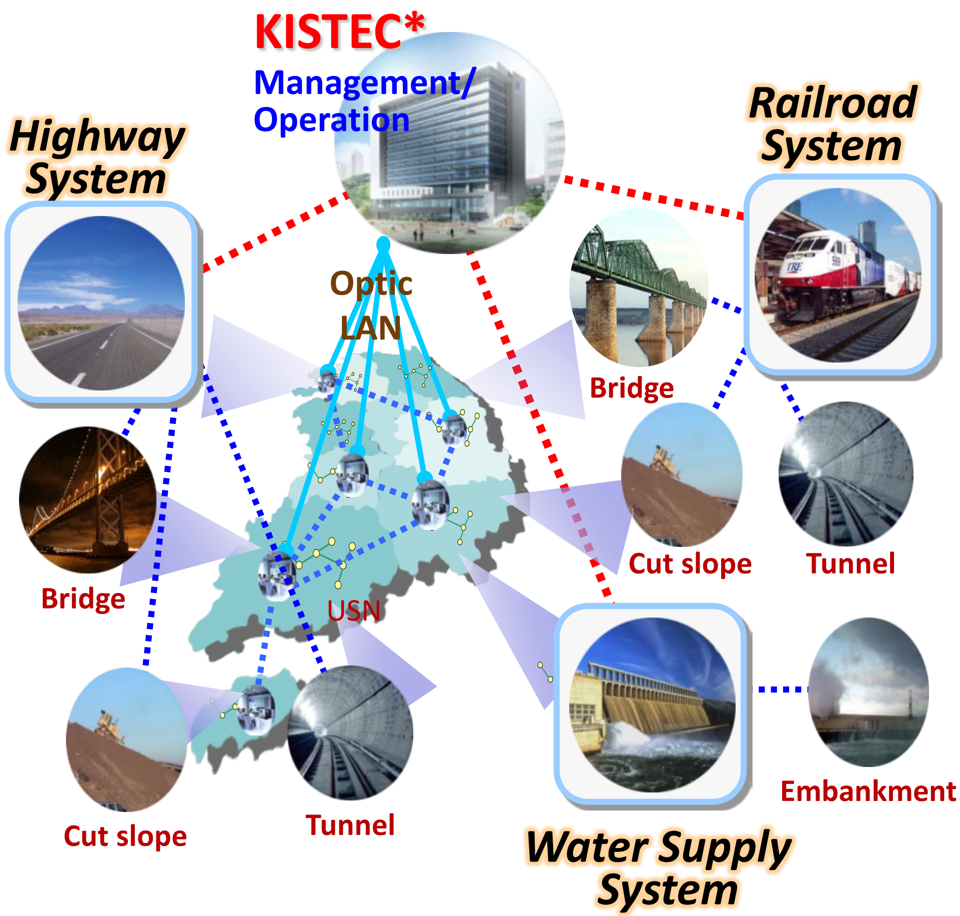


Tiltmeter

TRS Sensor

*TRS Sensors : Translation, Rotation and Settlement Sensors

National Networks for Safety Management of CE Structures



Railroad facilities:
Railroad, Bridge, Tunnel, Cut slope

Road facilities:
Bridge, Tunnel, Cut slope

Water Supply Systems:
Dam, River embankment,
Buried water supply pipes

Repair and Retrofit Maintenance

↓

Preventive Maintenance

Integrated Safety management of various facilities by KISTEC

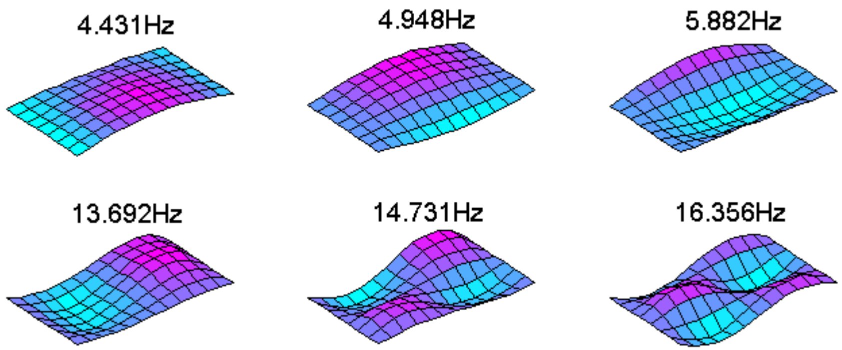
****KISTEC: Korea Infrastructures Safety Technology Corp.***

Global vs. Local Monitoring

• Global SHM

- Acceleration, Deflection, Freq, Modes
- **Accelerometers**, GPS, etc.
- Low frequency responses

- **Global vibration-based monitoring**



Applicable to Global Behavior, Insensitive to Structural Damage

• Local SHM / NDE

- Strain, Impedance, Guided waves,

- Optical fiber sensors, **Piezoelectric sensors,** Laser interferometer, etc.

- High frequency responses

- **Electro-mechanical impedance method**

- **Guided waves method**

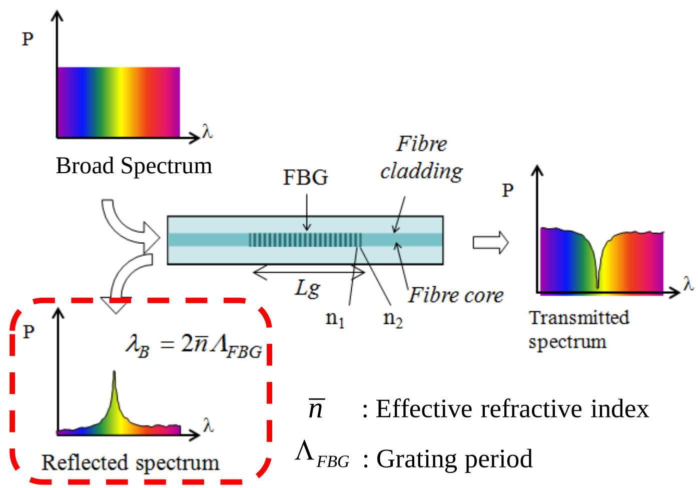
Applicable to Critical Members, Limited Sensing Range

Hybrid Monitoring & Data Fusion of Local & Global Information are Needed!!

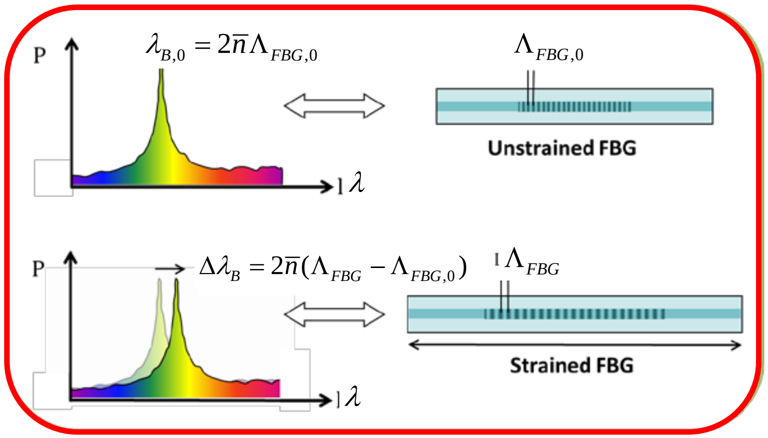
Optical Fiber Sensors

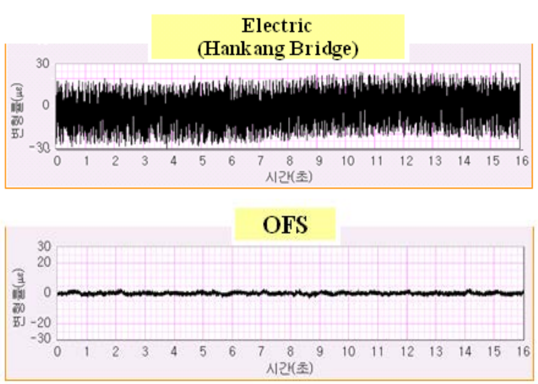
- Fiber Bragg Grating (FBG) Sensor

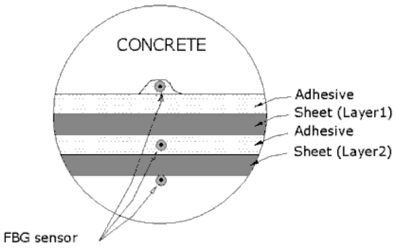
- No Electromagnetic Interference → Small Noise
- Multi-plexing Capability → Easy to lay-out to cover large area

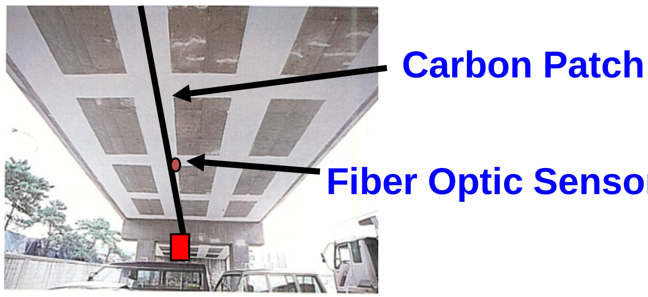


Reflected Spectrum







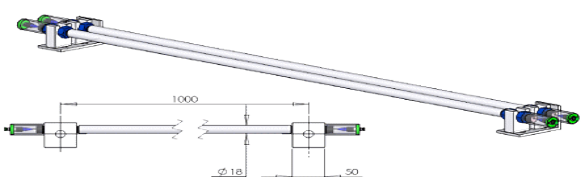


Smart Bridge Retrofit

(Courtesy of K-S. Kim, Hongik U.)

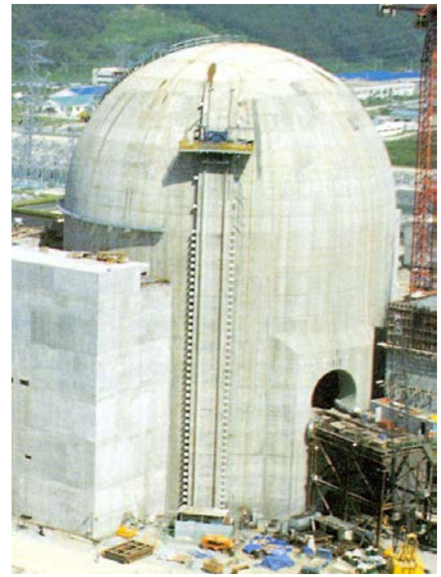
Applications of FBG Sensors

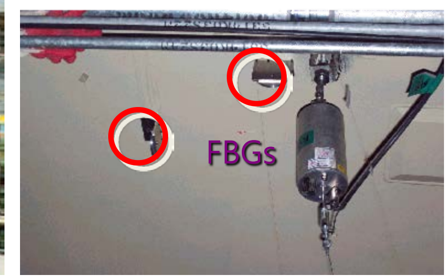
- **Tunnel Monitoring**

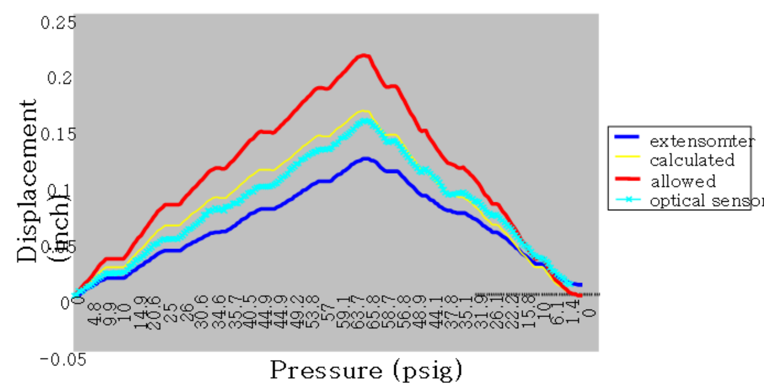


Long-gage FBGs

- **Integrity Test of NPP**





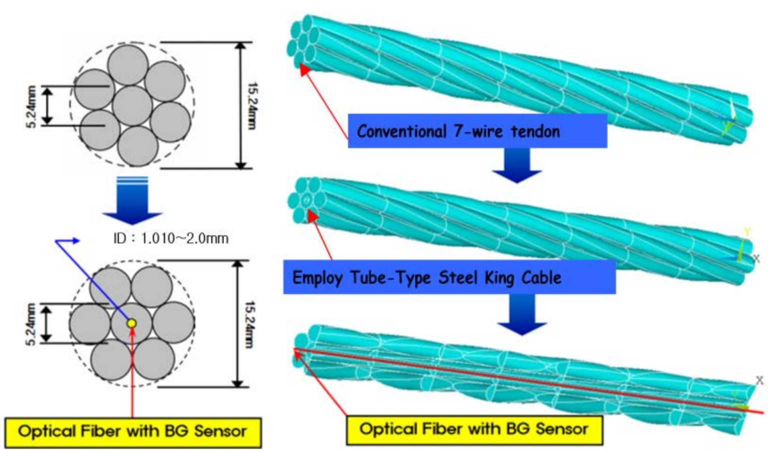


(Courtesy of YS Kim & JM Kim, Chonnam Univ.)

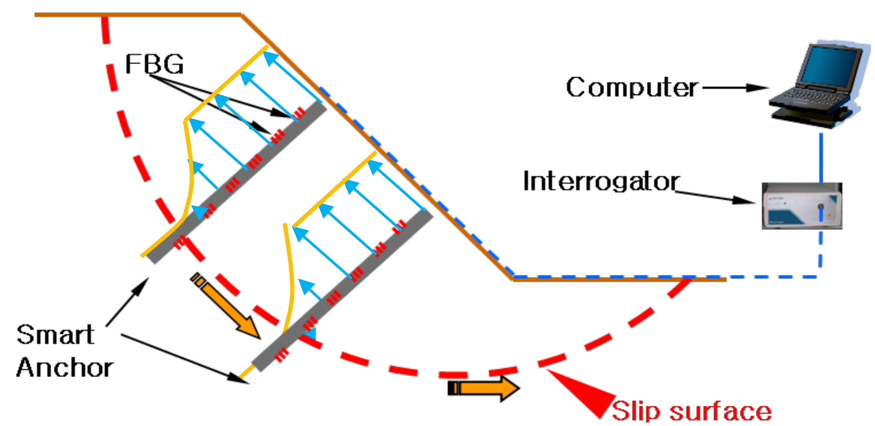
Smart Earth Anchor for Slope Monitoring

Slope Failure in Urban Areas

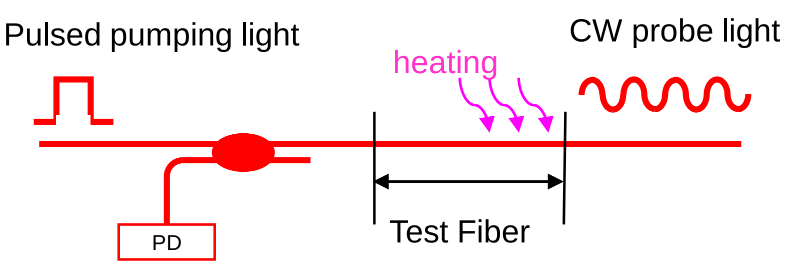
- ***Smart Earth Anchor : FBG Sensor Embedded Tendon***
  - -FBG sensor is embedded into a wire strand.
  - -Replacing the king wire with a steel tube with FBG



- Application of *Smart Earth Anchor* for Slope Monitoring



BOTDA* Sensor



***Brillouin Optical Time Domain Analysis:**

May cover 100km by a single line,
Good for dams, pipelines, foundation, etc.

Oil and Gas Pipeline Monitoring

Dam Monitoring

Oil and Gas Wall Monitoring

Bridge and Building Monitoring

Power Line Monitoring

Border Security Monitoring

Korea-China Research on SHM for Marine Pipelines

Offshore Pipelines for Oil Transport → *Corrosion, Free-spanning, Leakage, etc* → Oil Leakage, Environment Pollution, Economic Losses

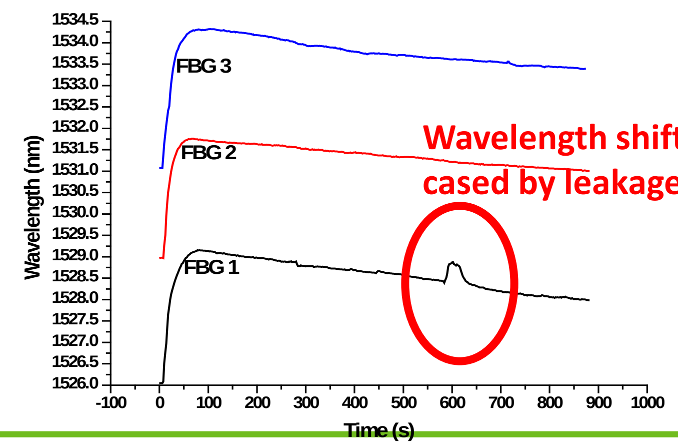
Accidents Around Us

April, 1997; Shengli, Bohai ,China
March, 2006; Shengli, Bohai ,China
May, 2006; The San Vicente Bay, Chile
May, 2010; Gulf of Mexico, USA

Offshore Pipeline Health Monitoring

Research Teams

- Participating Institutions : KAIST & Dalian U. of Tech.
- Coordinators : C.B. Yun (KAIST), Jing Zhou (Dalian U.T.)
- Period : July 2008 – June 2010
- Sponsored by NRF and NSFC



Research Scope

1. Damage mechanism : Free spanning & Oil leaking
2. Smart SHM of marine pipelines : Optical Fiber Sensors
3. Experiments : Small and large/real scale pipelines

(Courtesy of B. F. Spencer, Jr., UIUC)

Wireless Sensors and Network

Wired SHM System

Tsing Ma Bridge (Q. Ni, HK PloyU.)

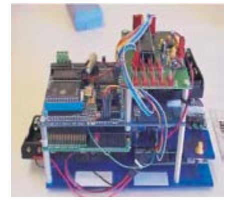
- 350 Sensing Channels
- Data acquisition/Processing/Analysis System
- Cabling Network System
- **$7.8 M-- $20,000/sensor**

Wireless Technology

- Hardwired systems are labor intensive costing a majority of the total system, whereas a **wireless system may drastically slash the cost of wired sensors.**

Various Wireless Sensor Nodes

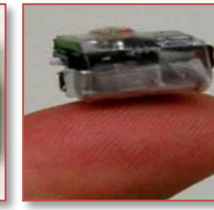
Stanford WiMMS



UC-Berkeley weC

Michigan U Narada

UCI Eco Node



Micro Strain G-Link

MEMSIC Imote2

Wireless Sensor Node

- On-board Computation for Diagnosis
- Sensor Self-diagnosis
- Low Cost & Small Size
- Energy Harvesting & Management
- Wireless Data Transmission

US-Korea-Japan Project on SHM of a Cable-stayed Bridge Test-bed Using Wireless Sensor Network

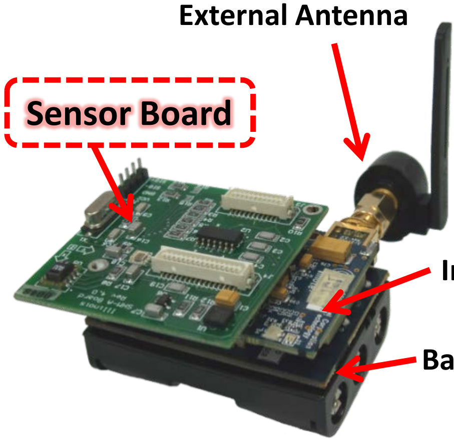
(2008-2011)

Objectives

- Field validation of wireless sensor network for SHM of a cable-stayed bridge in Korea
- Building of international SHM test-bed
- Participants :
  - **Korea: HJ. Jung, CB. Yun, & SJ. Cho, JW Park (KAIST), HK. Kim (SNU), & JW. Seo (Hyundai)**
  - **US: B.F. Spencer, Jr. & G. Agha (UIUC)**
  - **Japan: Y. Fujino & T. Nagayama (U. of Tokyo)**
- Sponsors: *NRF-Korea, NSF-US & STA-Japan*

(Courtesy of B. F. Spencer, Jr., UIUC)

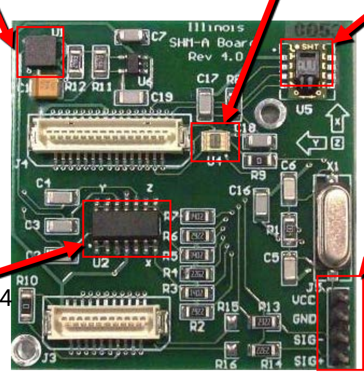
Hardware: Imote2 + SHM-A Board



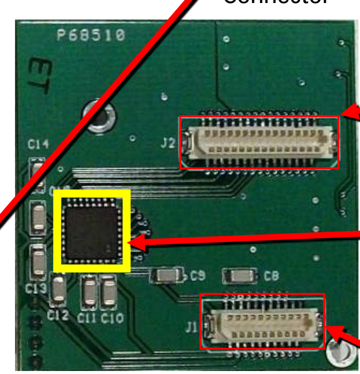
From MEMSIC (2010)

	MicaZ	Telos	Imote2
Microprocessor	Atmel ATmega128L	TI MSP430	Intel XScalePXA271
Clock speed (MHz)	7.373	8	**13-412**
Active Power (mW)	24	10	**44 @ 13 MHz**
Non-volatile memory (bytes)	128 K (Flash) + 512 K (EEPROM)	48K (Flash)	**32 M (Flash)**
Volatile memory (bytes)	4 K	1024K	**256 K + 32 M (SDRAM)**
Dimensions (mm) / Weight (g)	58*32*7 / 18	65*31*6 / 23	36 *48*9 / 12

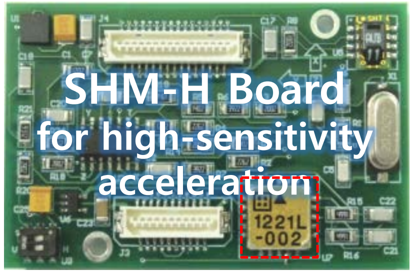
Various Sensor Boards

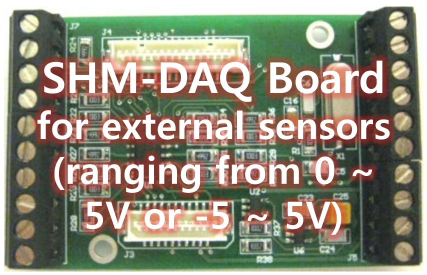


ISM400 Board (top)

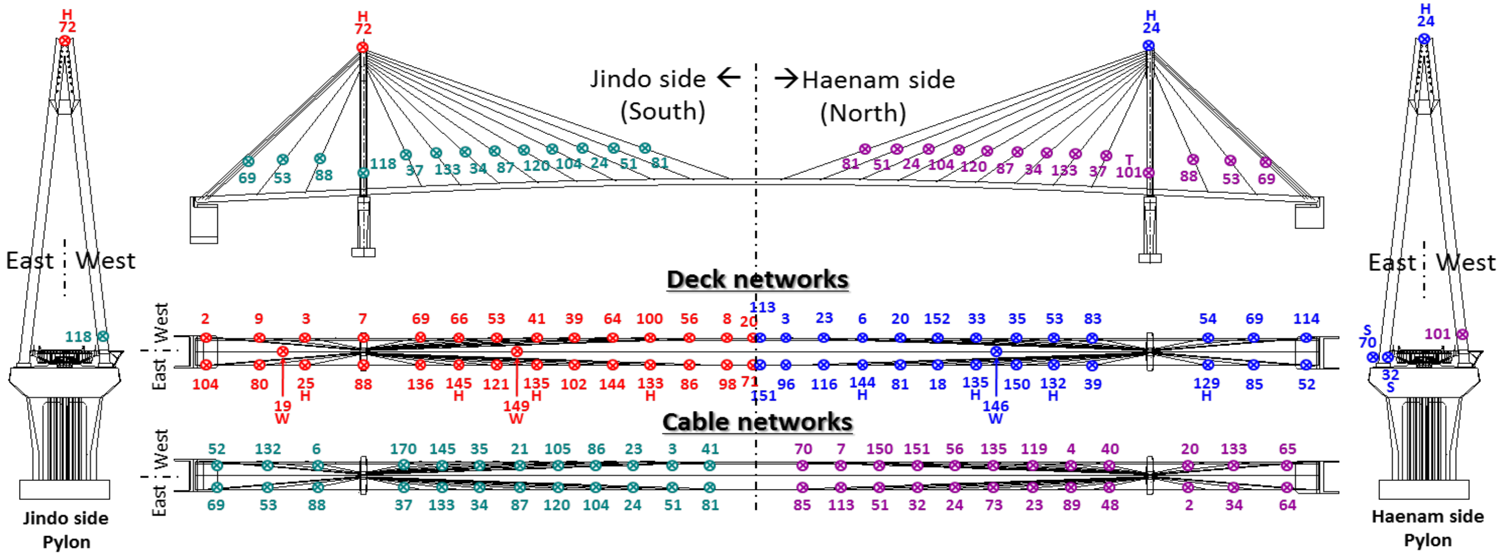


ISM400 Board (bottom)





Sensor Deployment (in 2010)



⊗ : Jindo Deck network (single hop)

⊗ : Jindo Cable network (multi hop)

⊗ : Haenam Deck network (single hop)

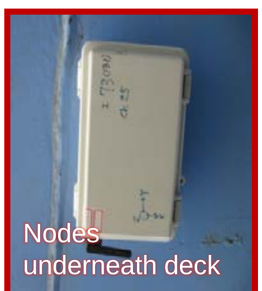
⊗ : Haenam Cable network (single hop)

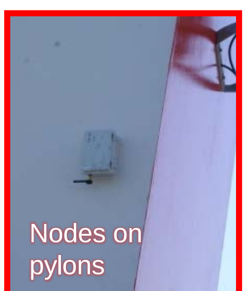
H : High-sensitivity (SHM-H)

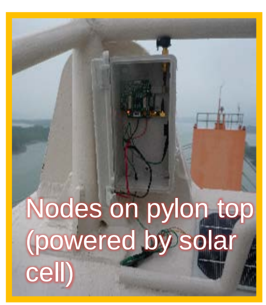
W : Anemometer (SHM-DAQ)

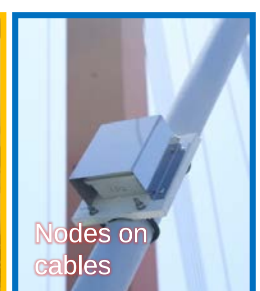
S : Strain sensor (SHM-S)

113 Wireless Smart Sensor Nodes
with **339** Sensing Channels

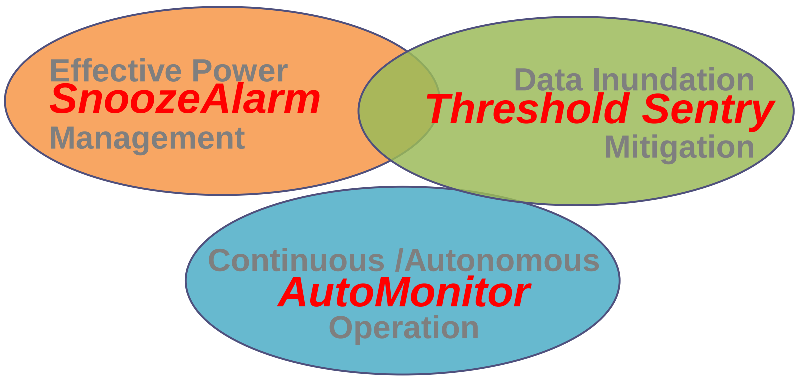








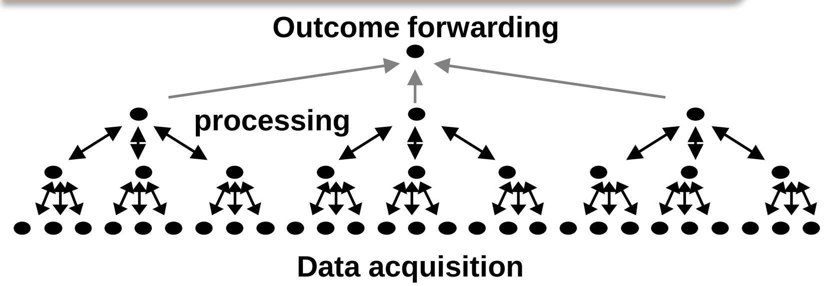
Full-scale Network Operation



Threshold Sentry

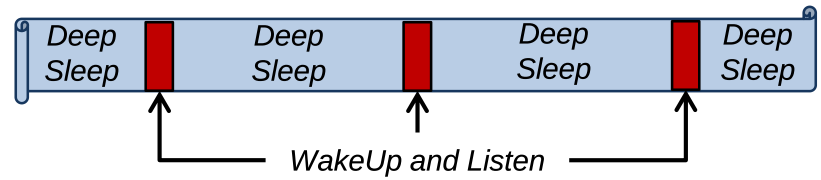
- Sentry Nodes wake up periodically
- If measured response **exceeds threshold**, all WSSN are awaken and start remote synchronized sensing
- **Vibration-Sentry** and **Wind-Sentry**

Hierarchical Sensor Network



SnoozeAlarm

- Default operation in power-saving *DeepSleep* mode
- Intermittent, short **WakeUp and Listen** allow remote nodes to be accessed by base station

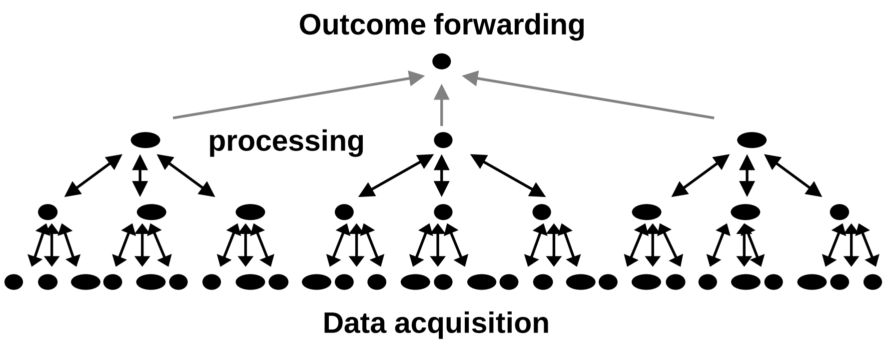


AutoMonitor

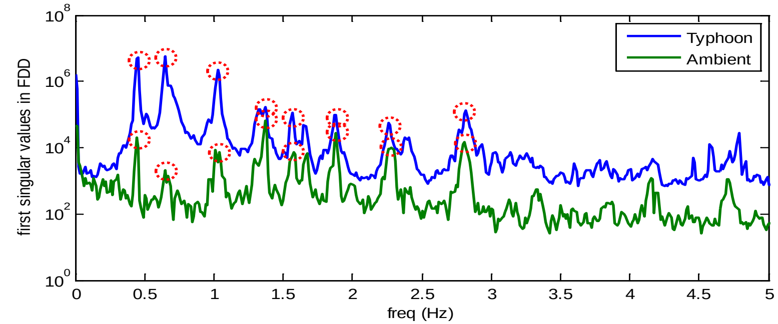
- Network management software
- Automated coordination of large WSSN

Energy Harvester

Decentralized Data Aggregation

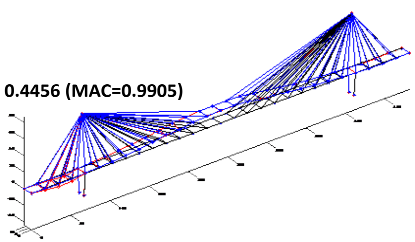


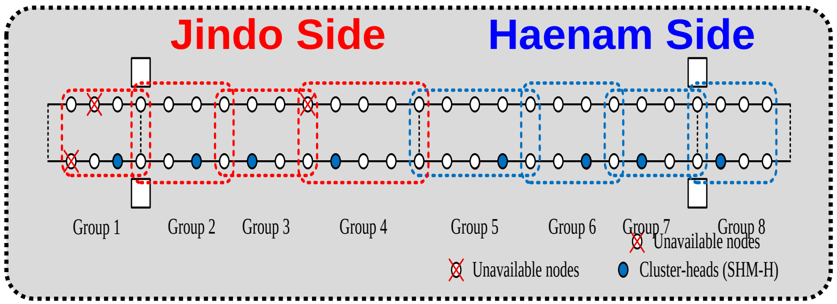
Frequency Identification by FDD

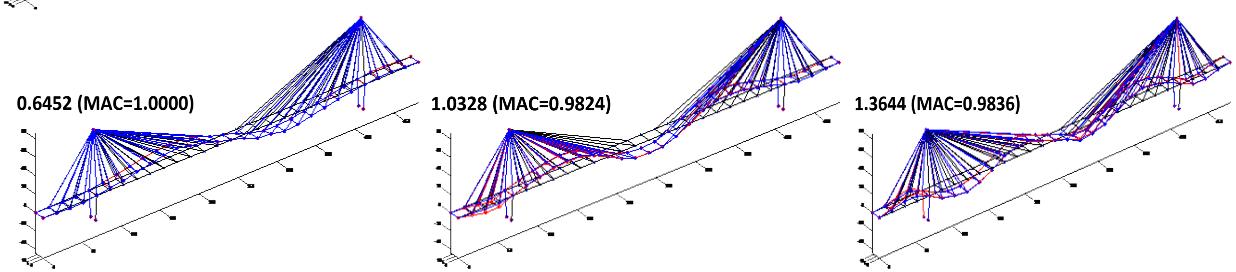


Decentralized Identification of Modal Properties

Decentralized modal analysis
Centralized modal analysis







No.	Natural Frequencies (Hz)		
1	0.446	0.440	0.442
2	0.645	0.659	0.647
3	1.033	1.050	1.001
4	1.364	1.367	1.247
5	1.575	1.587	1.349
6	1.672	1.660	1.460
7	1.879	1.856	1.586
8	2.276	2.319	2.115
9	2.802	2.808	2.561
	(Wireless)	(Wired)	(FEM)

Cable Tension Monitoring

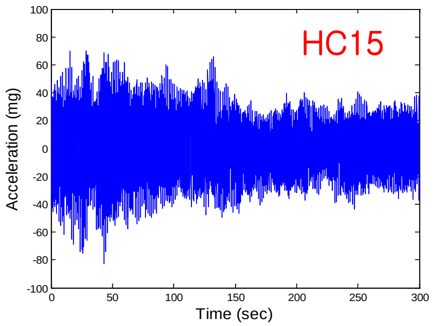
Vibration-based Tension Force Estimation

$$\left(\frac{f_n}{n}\right)^2 = \frac{T}{4mL_{eff}^{\ 2}} + \frac{EI\pi^2 n^2}{4mL_{eff}^{\ 4}} = a + bn^2$$

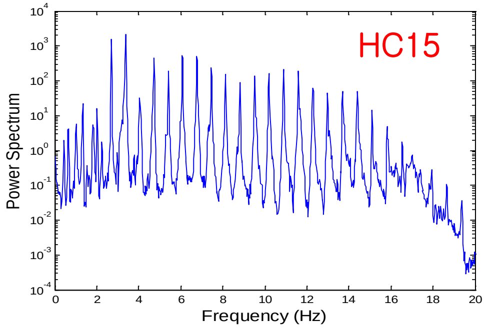
Linear regression to find *a* and *b*

$$T = 4mL_{eff}^{\ 2}a$$

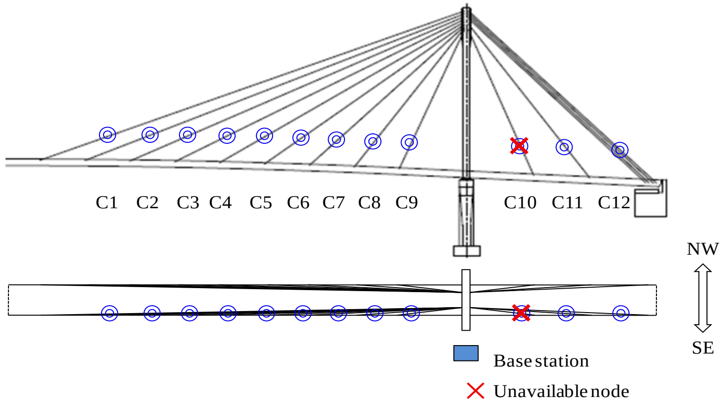
Cable Acceleration



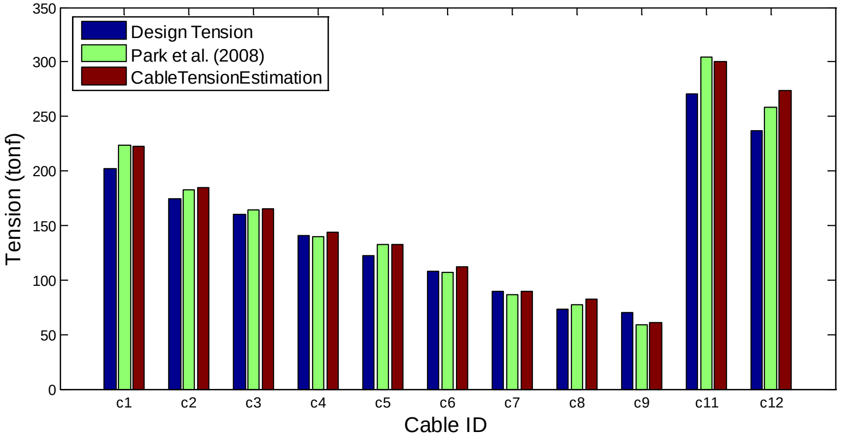
Frequency ID. (FDD)



Cable Tension Obtained by Embedded Processing



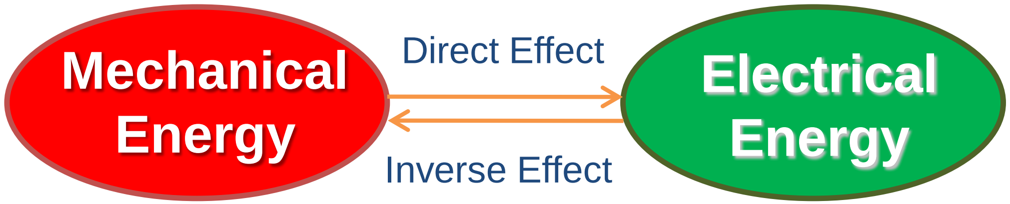
[Cable ID]

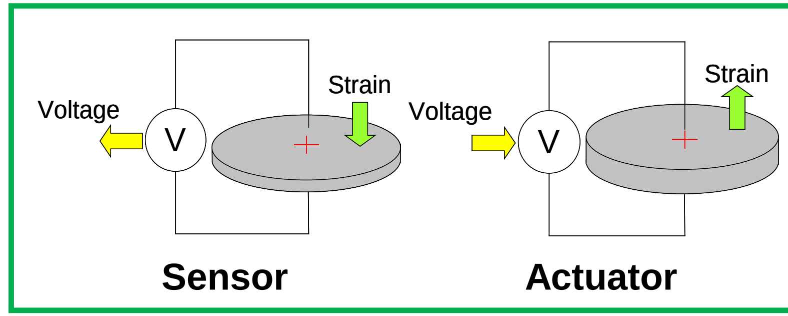


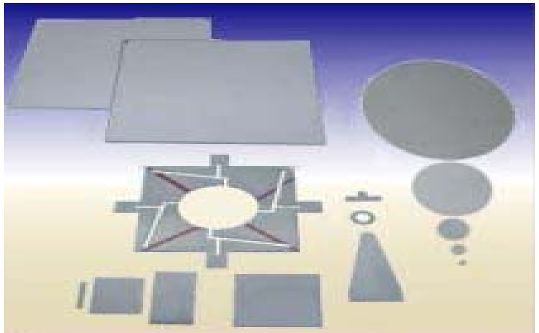
[Cable tension comparisons]

Piezoelectric Material & Active Sensors

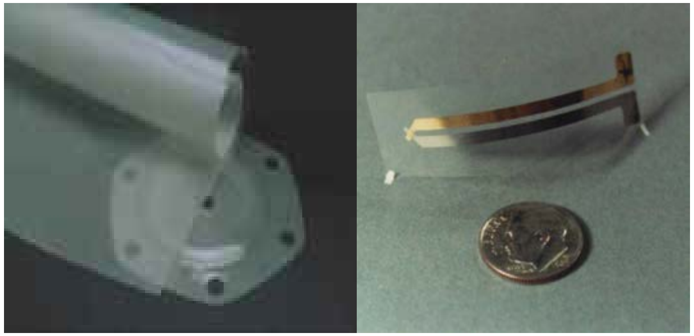
❖ *Piezoelectric Materials*



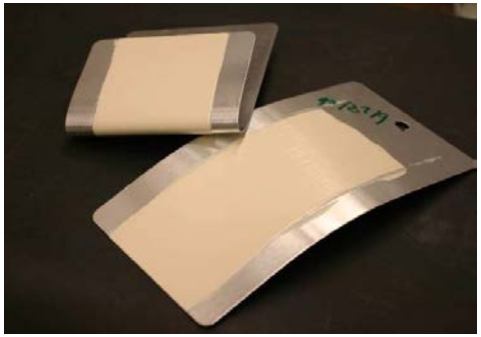




PZT Sensors

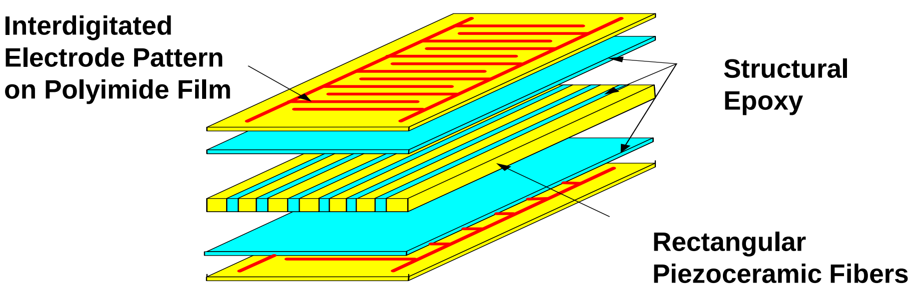


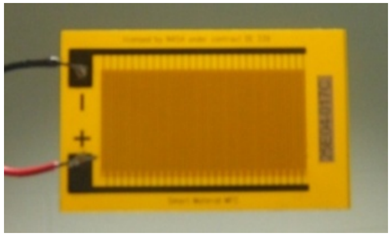
PVDF Sensors

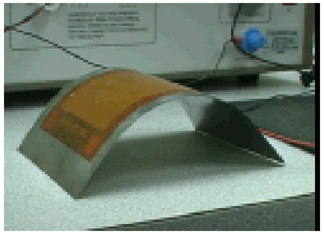


Piezo-Paint Sensors (Y. Zhang)

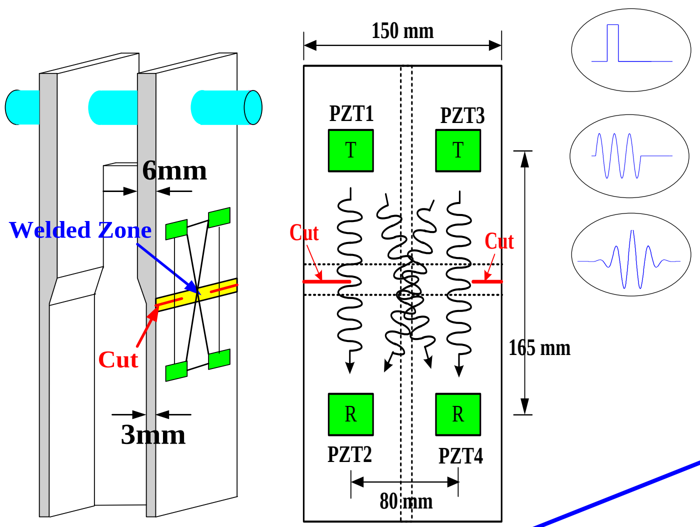
*** MFC (Macro Fabric Composite) Sensors, Developed by NASA**

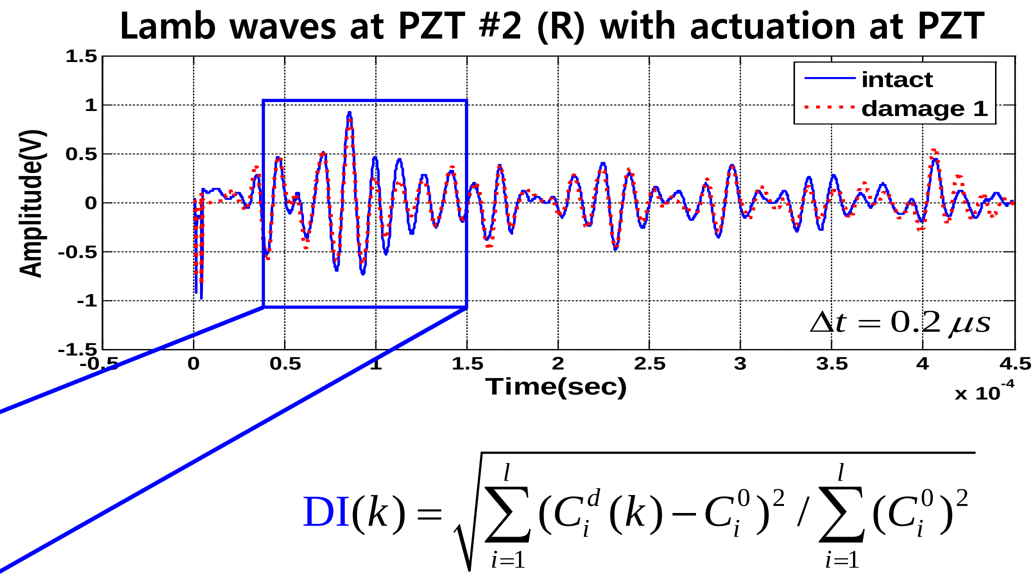






Guided Waves-based Local SHM

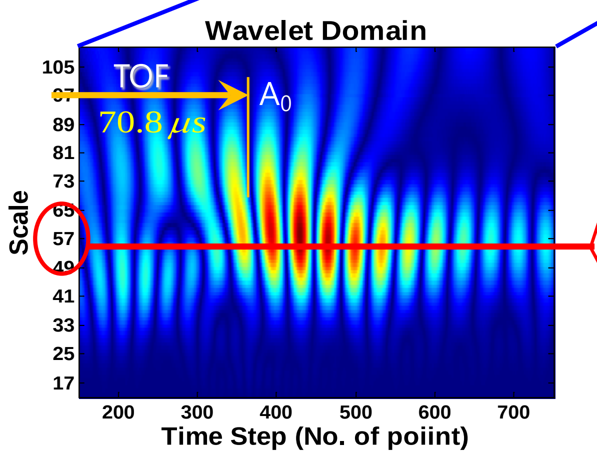


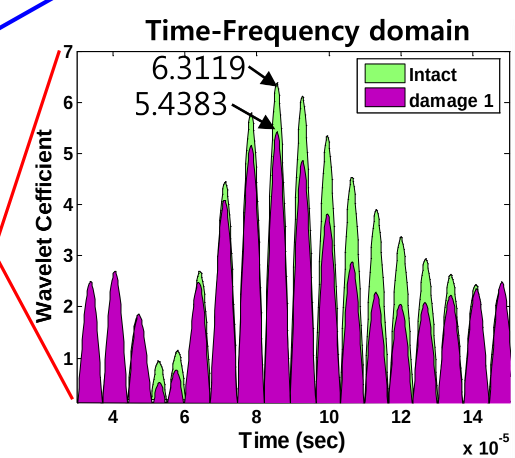


$$\mathrm{DI}(k)=\sqrt{\sum_{i=1}^{l}(C_i^d(k)-C_i^0)^2 \Big/ \sum_{i=1}^{l}(C_i^0)^2}$$

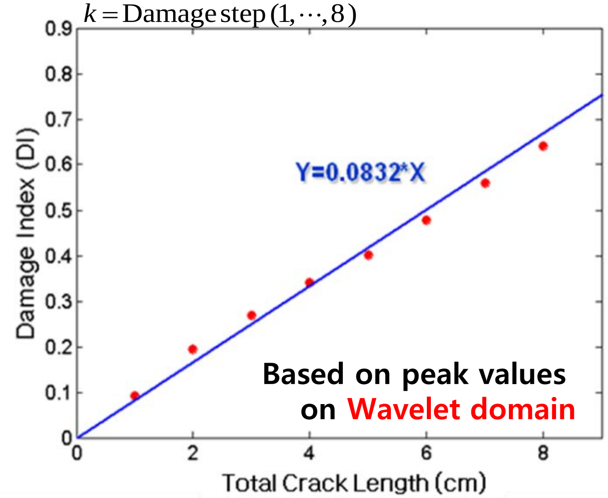
l = No. of pitch-catch combination

k = Damage step $(1,\cdots,8)$



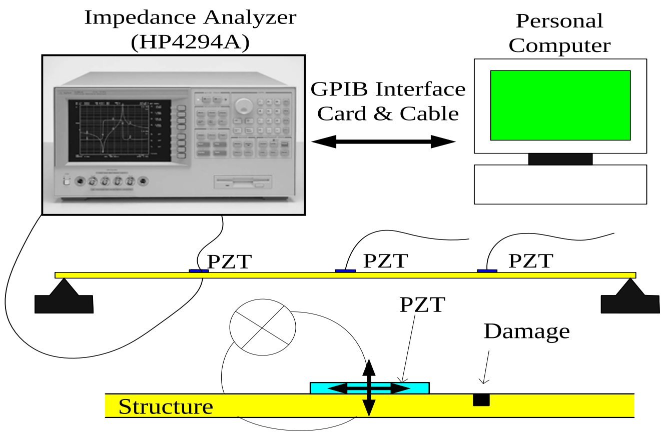


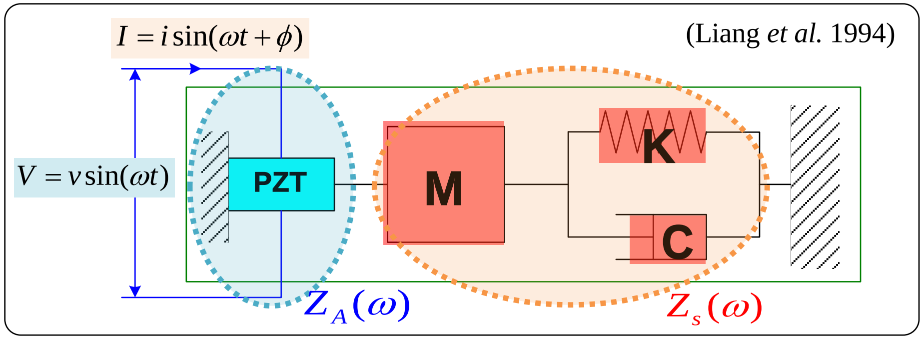
Cross Section at Scale #57
(Central Frequency=72 kHz)



Impedance-based Local SHM

❖ *Impedance Measurement System*

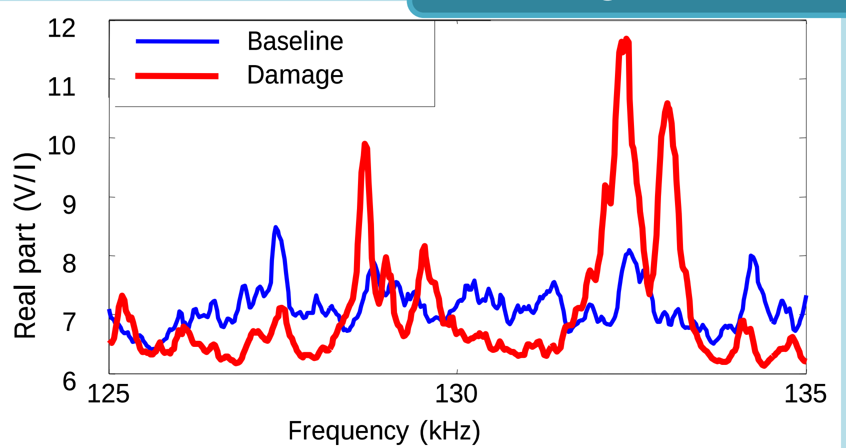




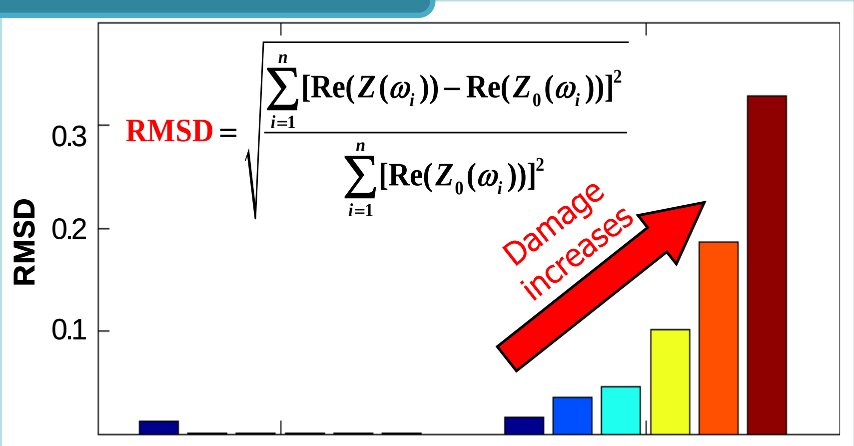
- Electro-Mechanical Impedance :

$$Z_{total}(\omega) = [i\omega C(1-\kappa_{31}^2 \frac{Z_s(\omega)}{Z_A(\omega)+Z_s(\omega)})]^{-1}$$

Damage Detection w/ RMSD Index



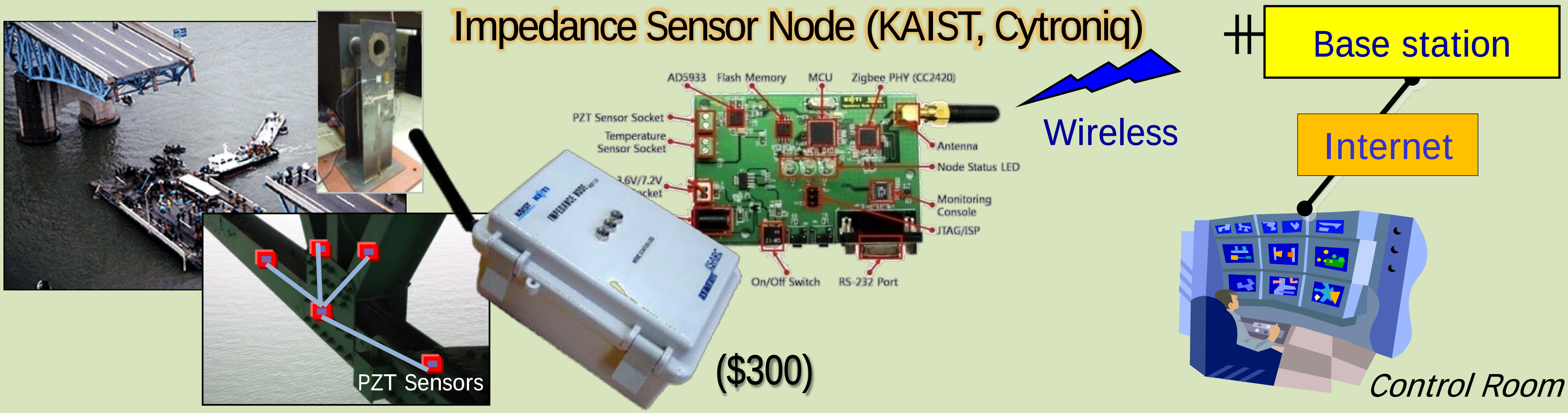
Impedance Signals w/o & w/ damages

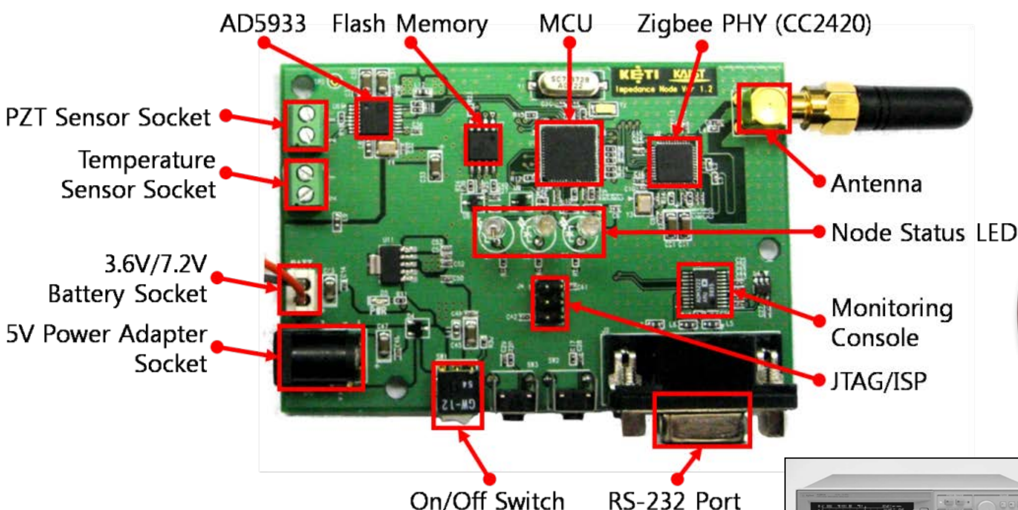


$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}[\text{Re}(Z(\omega_i)) - \text{Re}(Z_0(\omega_i))]^2}{\sum_{i=1}^{n}[\text{Re}(Z_0(\omega_i))]^2}}$$

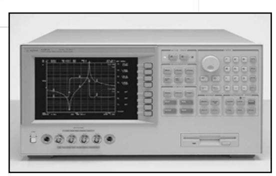
Baselines Damages

Wireless Impedance Sensor Node

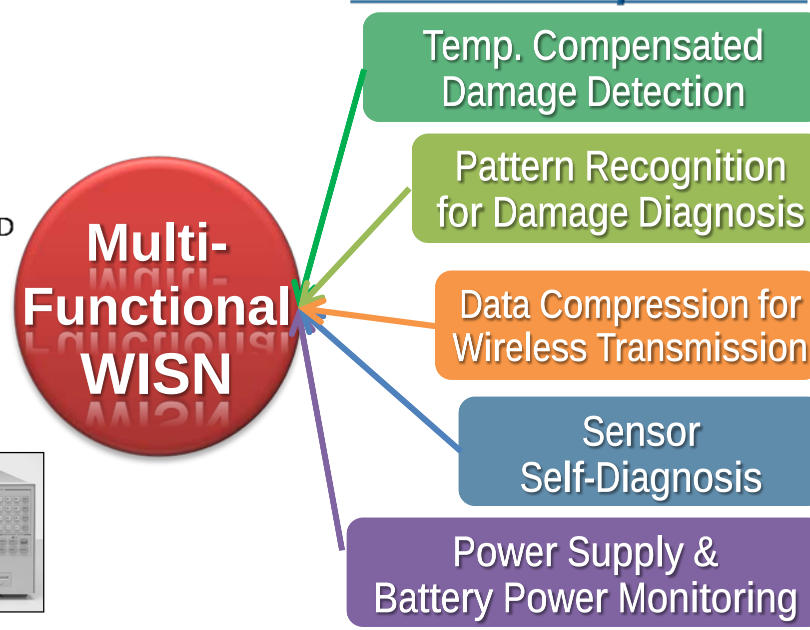




*** Impedance Analyzer (HP4294A) : $41,000***

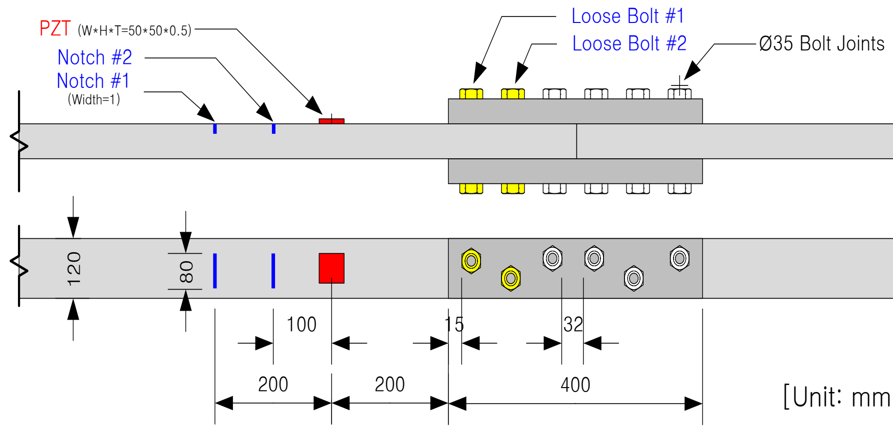


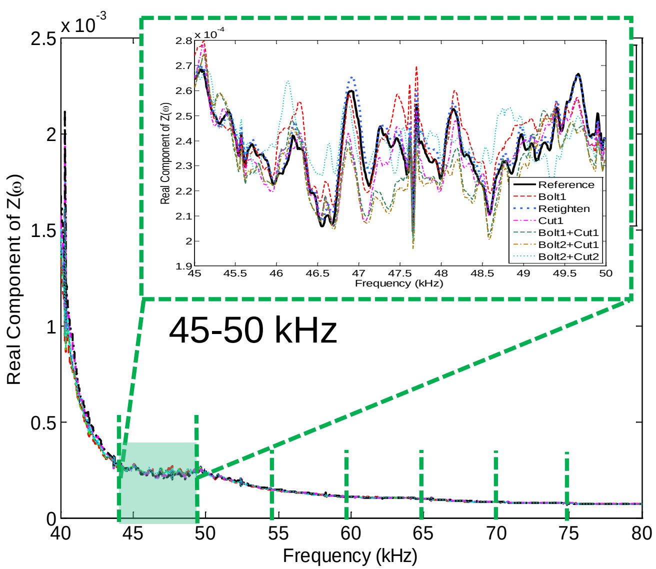
On-board Operation



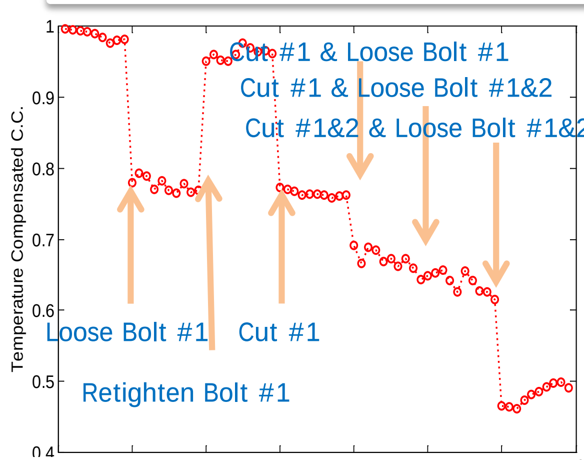
Autonomous Frequency Range Selection for Diagnosis

❖ *Loose Bolt and Crack Detection on Bridge* *(Korea Expressway Corp.)*

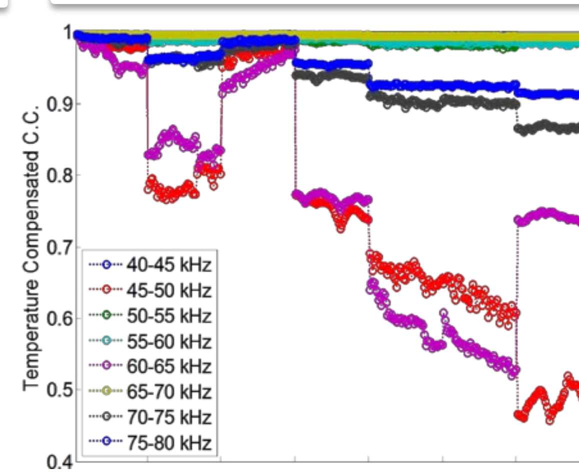




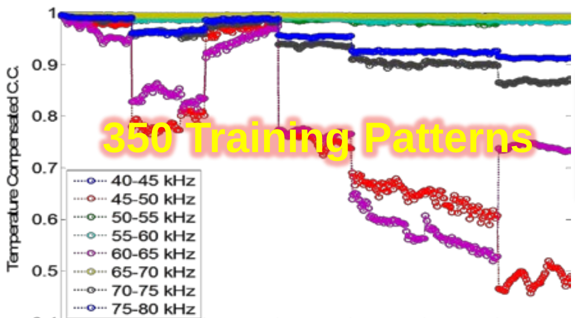
For Single Freq. Range (45-50 kHz)



For Multiple Freq. Ranges (40-80 kHz)



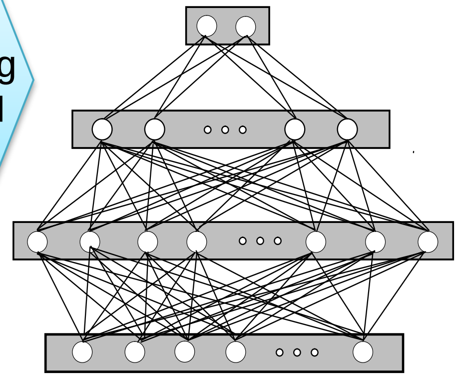
Damage Diagnosis Using Neural Network



CC values for Various Frequency Range with 5 kHz intervals

Training for NN

Damage Type & Severity



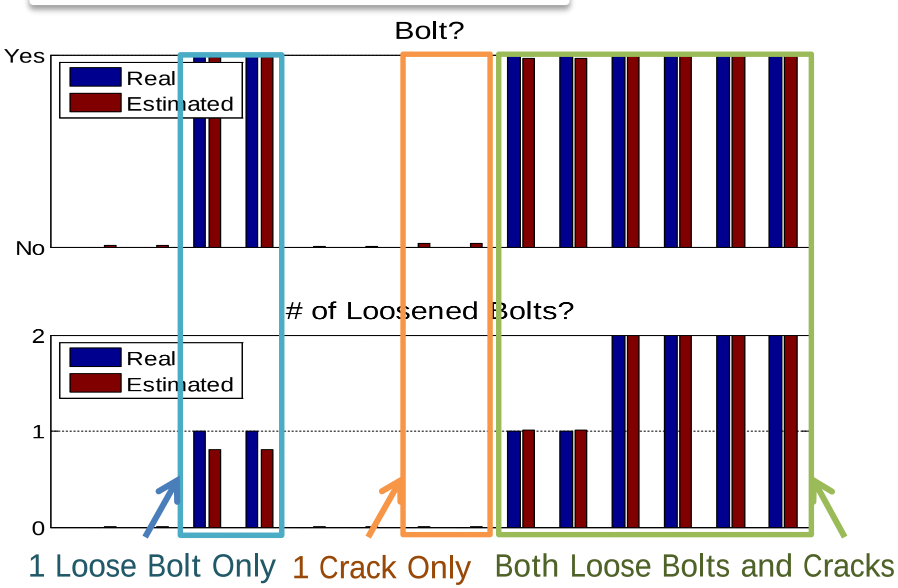
CC Values in 8 Frequency Ranges

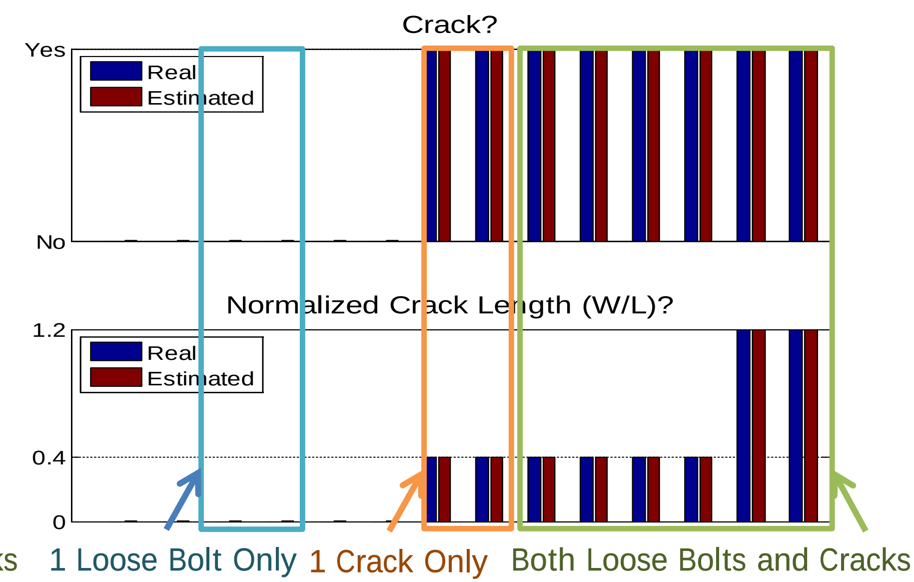
Damages	Output 1 **Type**	Output 2 **Severity**
No Damage	[0 0]	[0 0]
Loose Bolt Only	[1 0]	[N 0]
Crack Only	[0 1]	[0 W/L]
Multiple Damages (Loose Bolt and Crack)	[1 1]	[N W/L]

* N : No. of Loose Bolts
* W/L : Normalized Crack Length

14 Test Cases

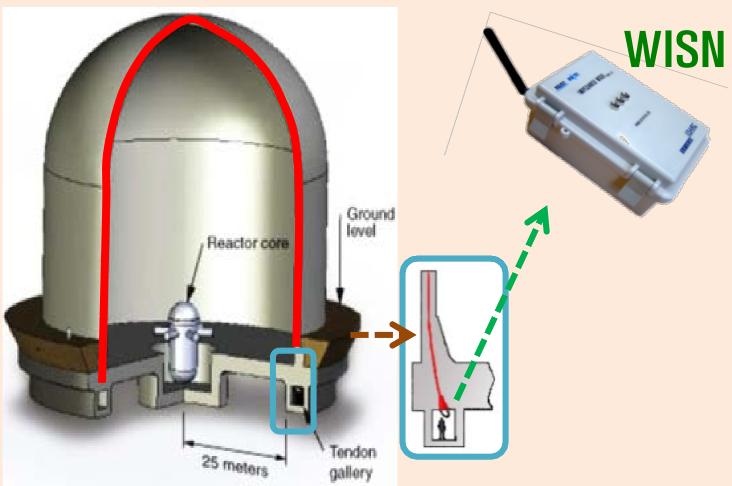
2 Patterns for each test damage case



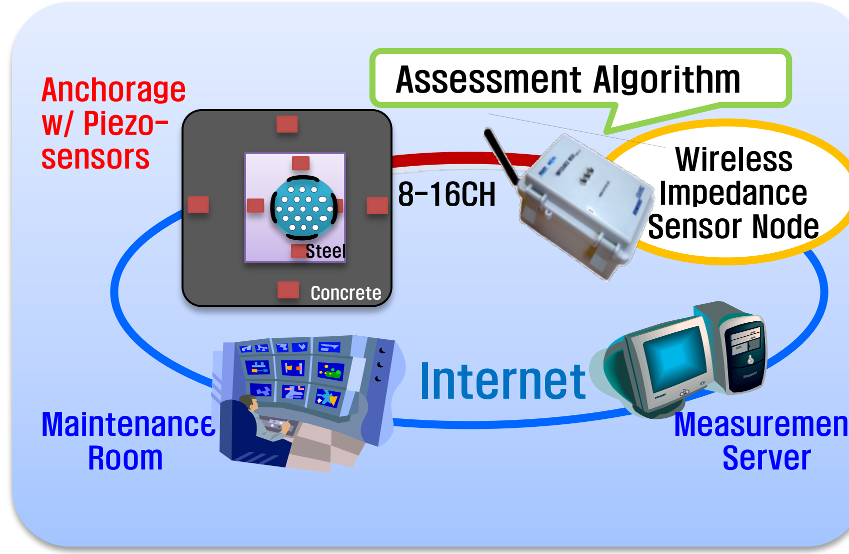


Tendon Force Monitoring by Multiple Piezo-sensors

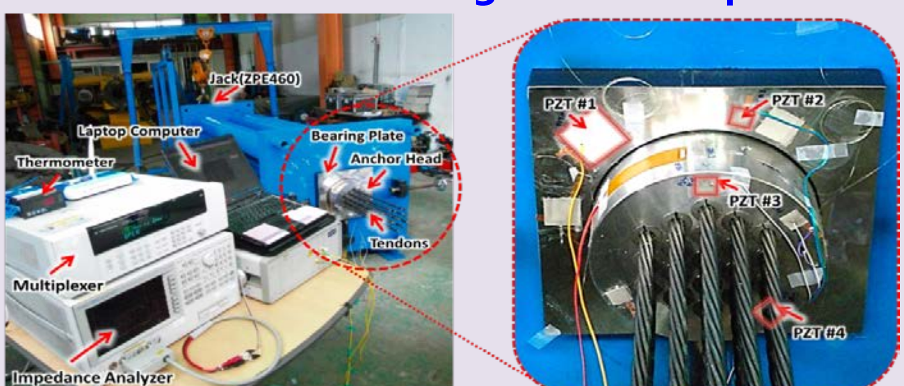
Nuclear Containment Structure



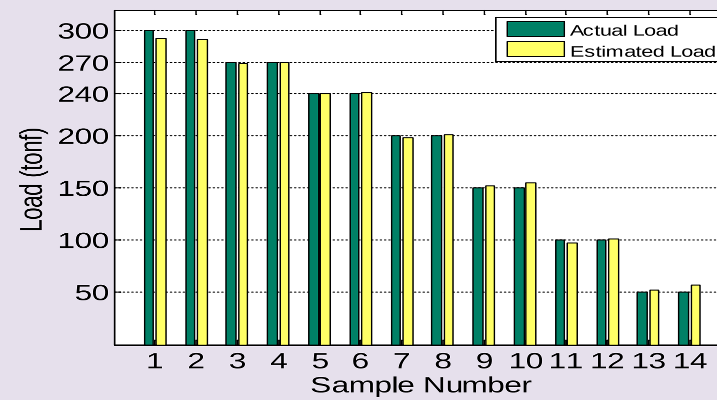
Wireless Tendon Monitoring



Anchor Head Monitoring with Multiple PZTs

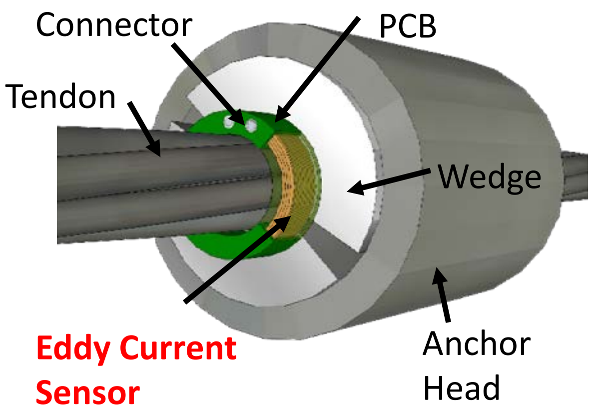


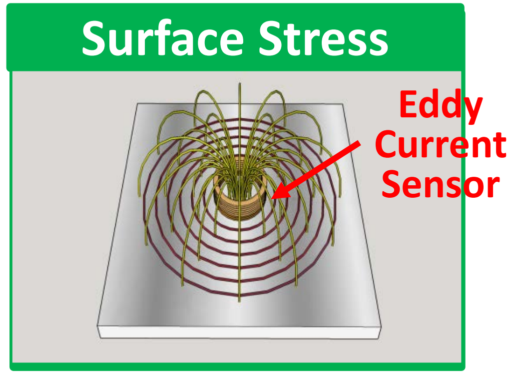
Tension Loss Estimation

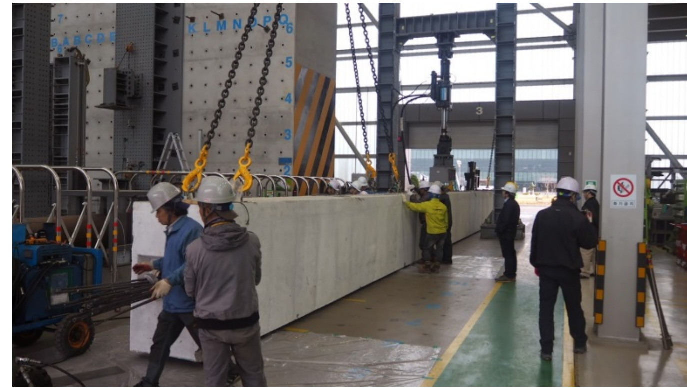


Eddy Current Technique for Tendon Force Monitoring

(JM Kim, J Lee, & H Sohn at KAIST)

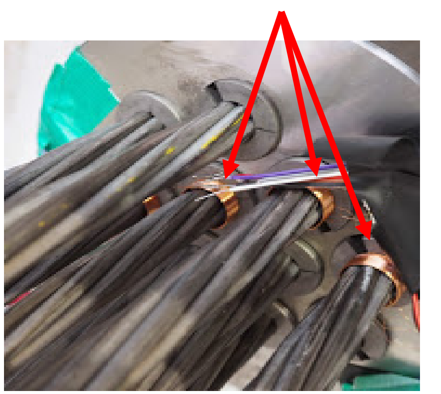






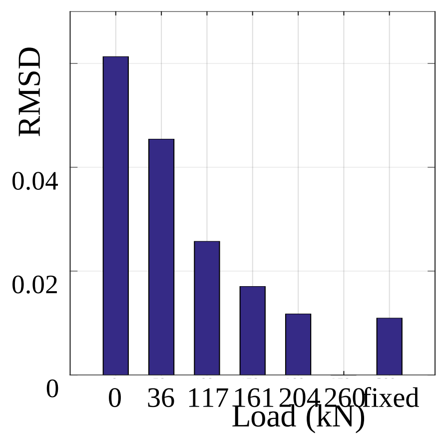
Current ➡ Magnetic Field ➡ Eddy Current ➡ Stress Level

Eddy Current Sensors

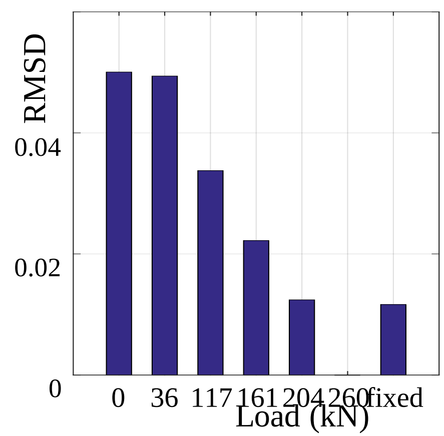


30 m PC Girder

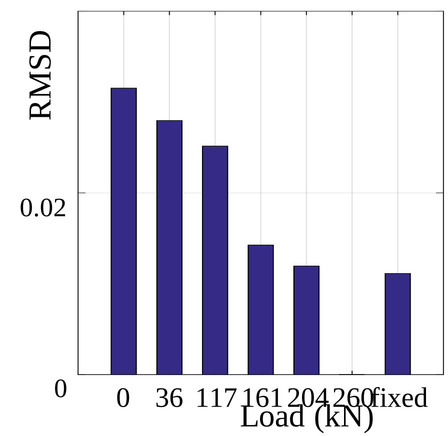
1st Sensor



2nd Sensor



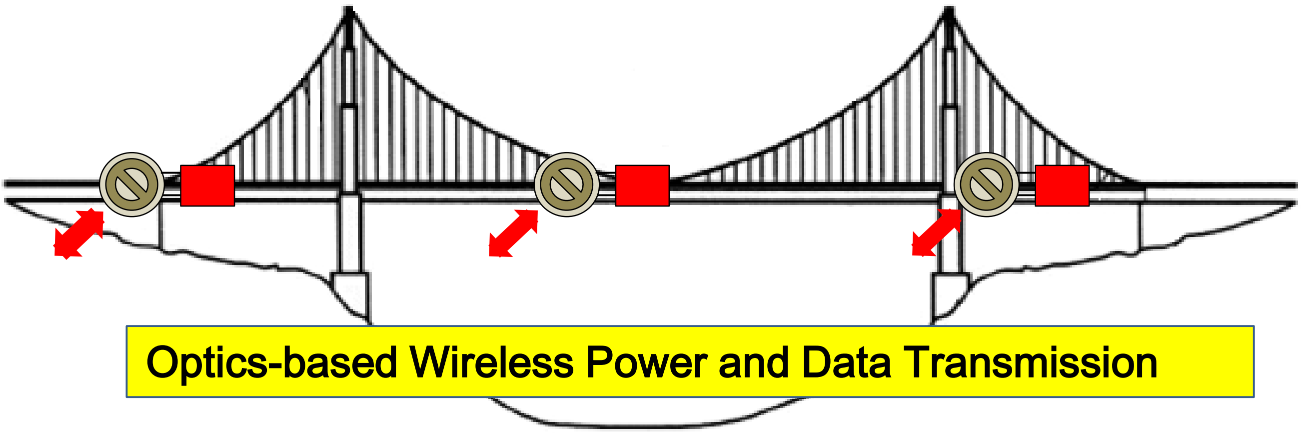
3rd Sensor

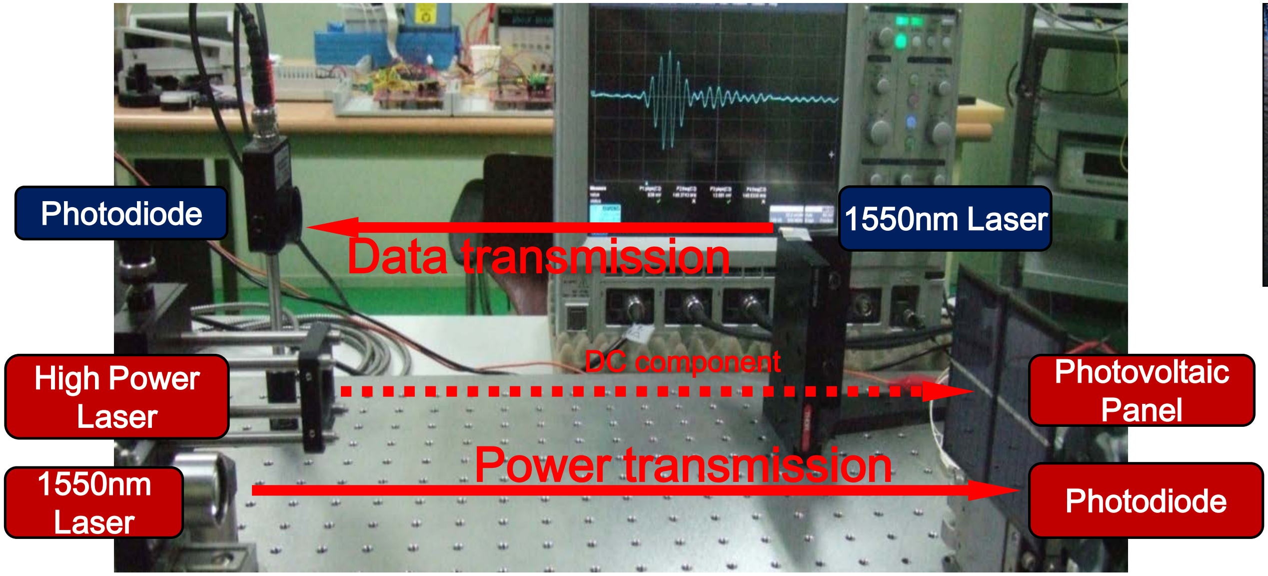


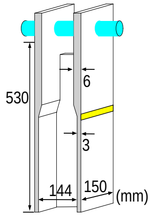
Non-contact Sensing Using Laser

(H Sohn & HJ Park at KAIST)

Unmanned Inspection Robot





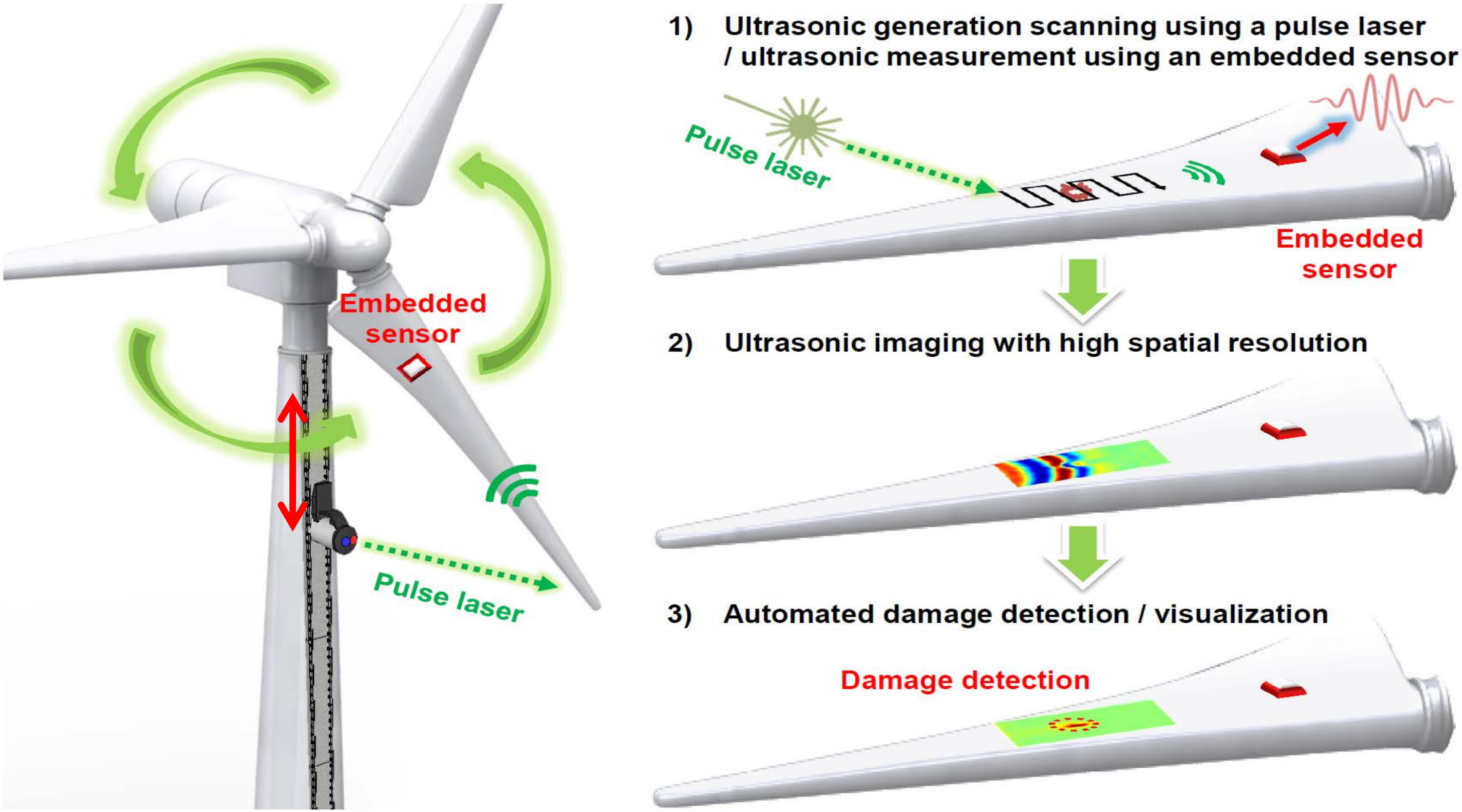


1/8 Model for a Steel Member

Noncontact Monitoring of Wind-turbine Blades

(H Sohn & YK Ahn at KAIST)

Reference-free Method for Damage Identification



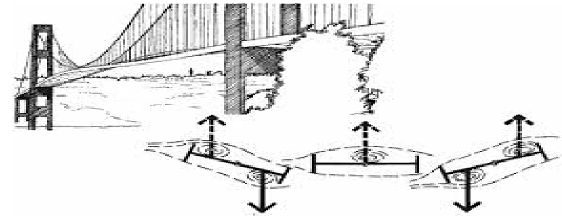
Structural Control and Smart Retrofit

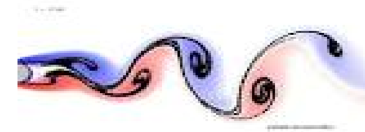
(Courtesy of B. F. Spencer, Jr., UIUC)

Disastrous Vibration of Bridge: Flutter

Old Tacoma Narrows Bridge (1940)



Vortex



Flutter at Wind of 64 km/h.
(Design Wind= 190km/h)

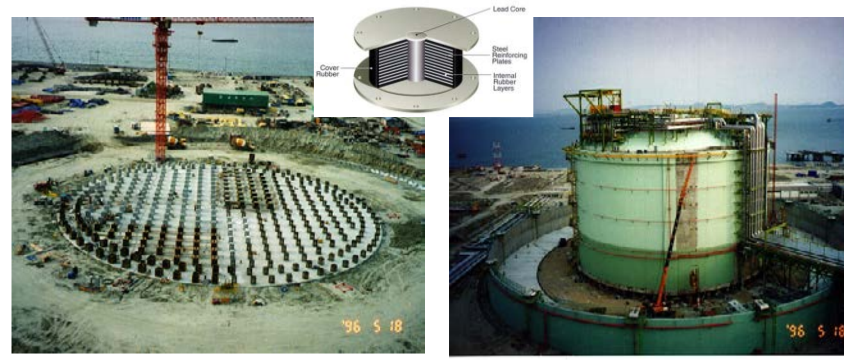
Current Bridges with Stiffening Truss Deck

❖ Flutter : Aerodynamic Instability due to negative damping effect

[Countermeasure: Aero-dynamical Re-design of Deck]

Tall and Slender Structures

- **More vulnerable to dynamic loadings such as wind, earthquakes, waves, traffic, machine vibrations, etc.**
- **Measures for Response Modification and Structural Control are needed to reduce the dynamic load effects for operational and survival conditions.**



Supplemental Damping Devices

Passive Systems

Non-controllable
No power required
Less effective but reliable

(e.g., Viscous Damper, Base-isolator, TMD, TLCD, …)

Active Systems

Controllable
Significant power required
Effective but less reliable

(e.g., AMD, HMD, Active Tendon …)

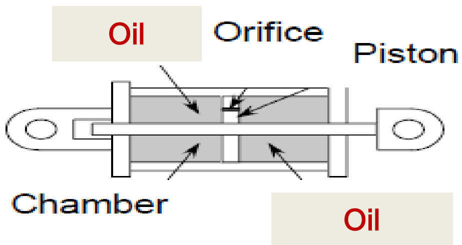
Semi-active Systems

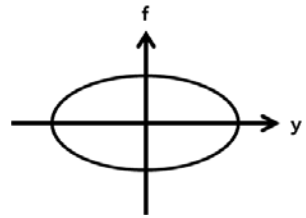
Controllable
Little power required
Effective and reliable

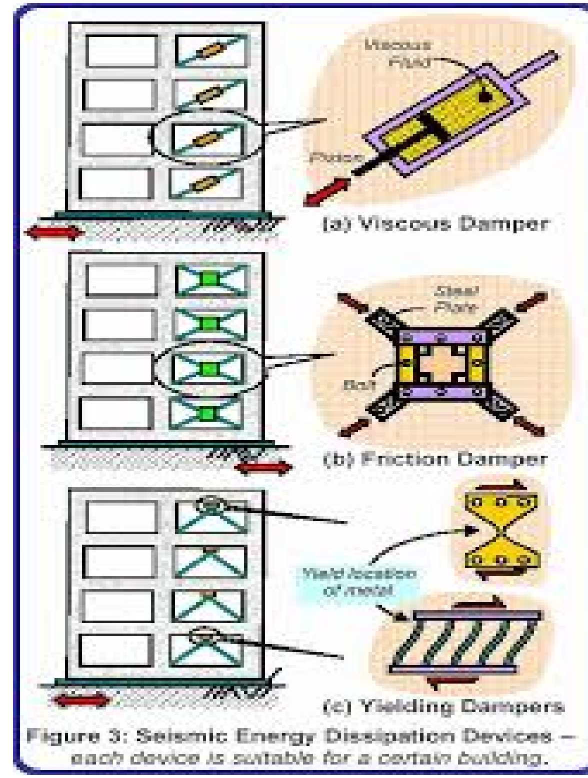
(e.g., MR damper, Variable Orifice Damper, Variable Stiffness Damper, …)

Conventional Dampers

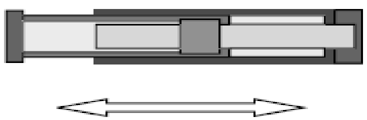
Viscous Type

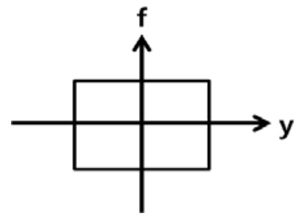




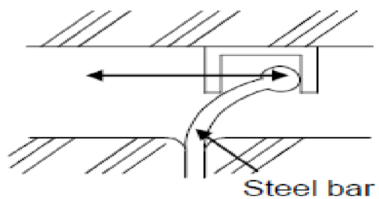


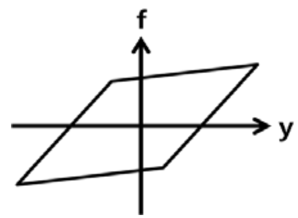
Friction Type



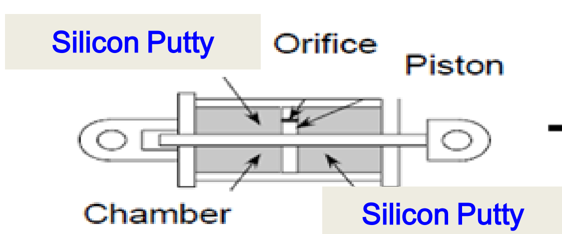


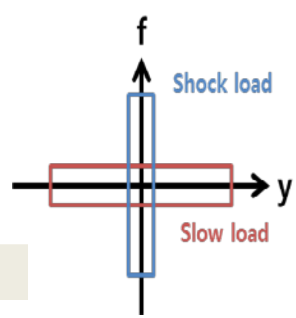
Elasto-plastic Type

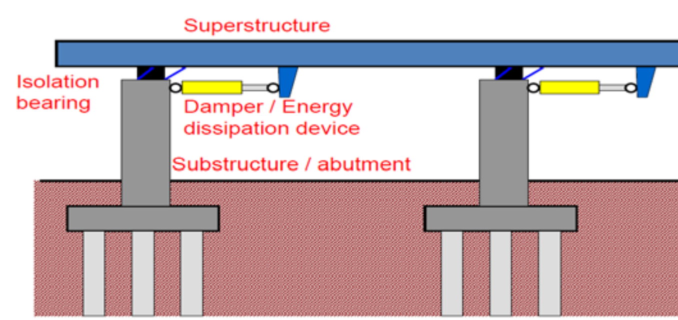




Lock-up Type

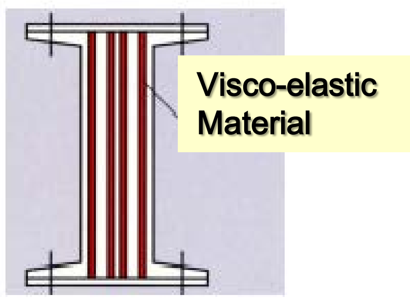




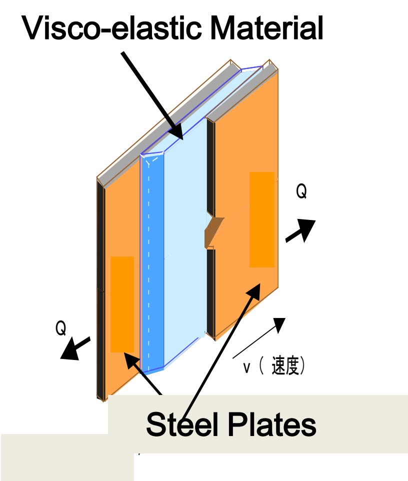


Visco-Elastic & Steel Dampers

Visco-Elastic Dampers

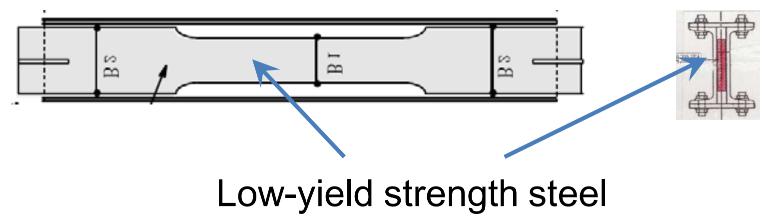


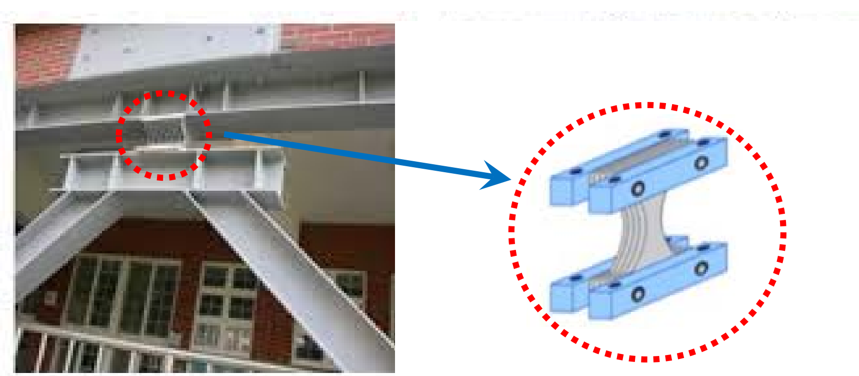
Brace Type



Wall Type

Steel Dampers



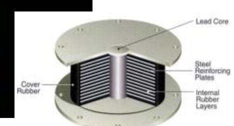


(Courtesy of Y-S. Kim, TE Solution)

Base Isolation

Building Models

https://www.youtube.com/watch?v=ZqlXp3czrrM

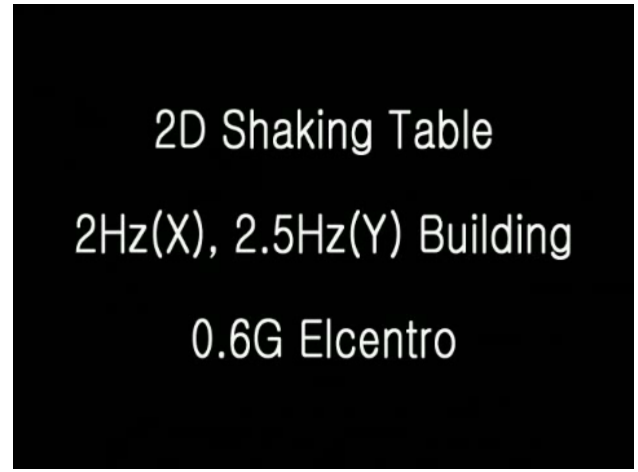


On Fixed Base

Base-isolated

Base-isolation Bearing

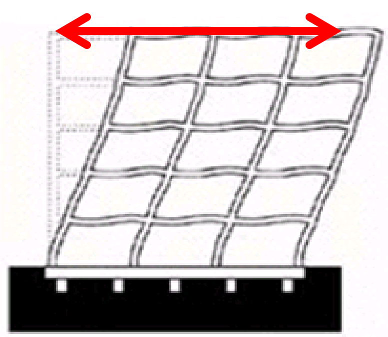
Display-Tables



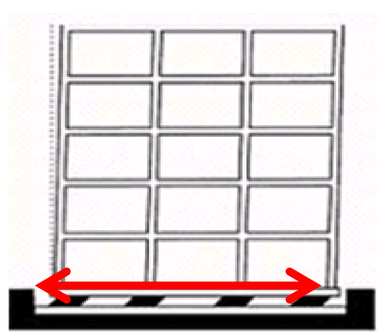
On Fixed Base

Base-isolated

On Fixed Base



Base-isolated



Dynamic Amplification

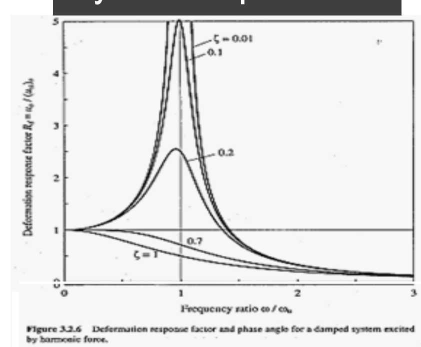
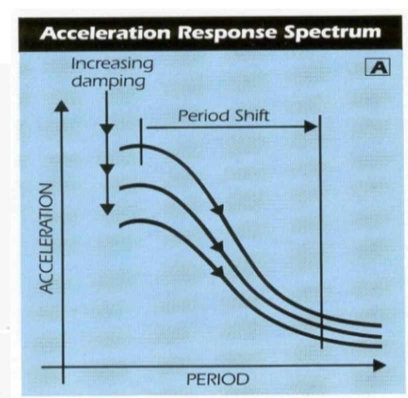
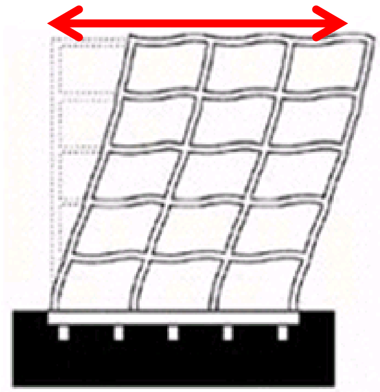


Figure 3.2.6 Deformation response factor and phase angle for a damped system excited by harmonic force.

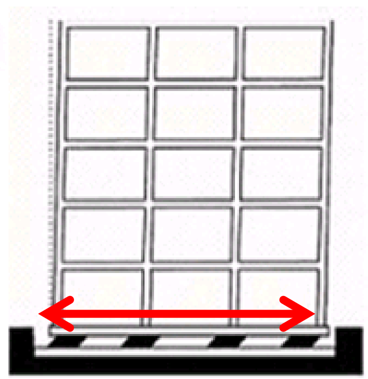
Acceleration Response Spectrum



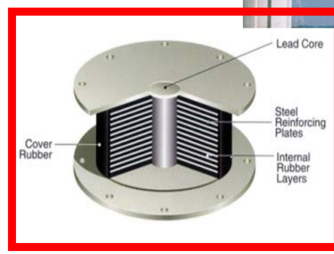
Base Isolated Buildings & Bridges: LRBs



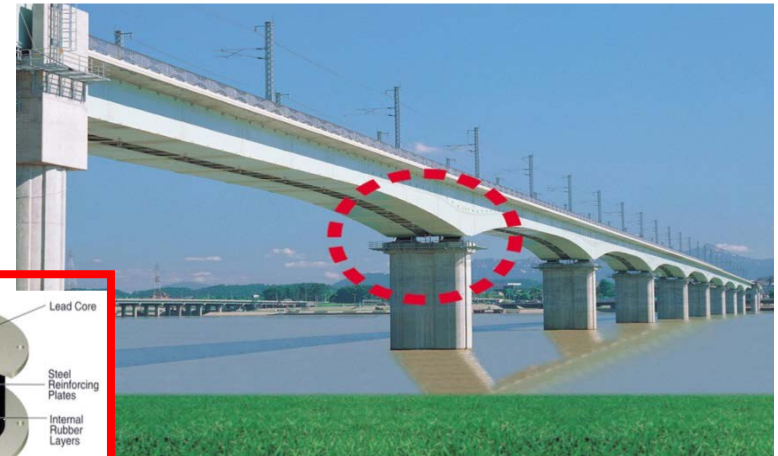
Earthquake-resistant Building



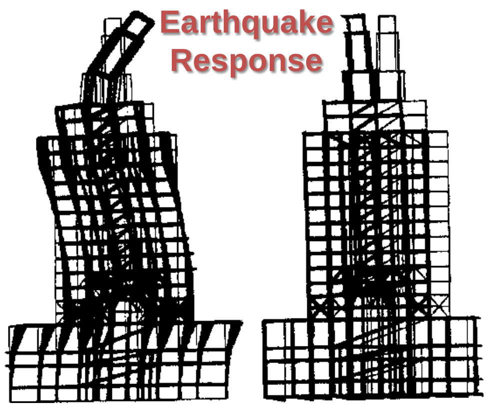
Base-isolated Building



Dangsan Bridge, Seoul



Seismic Retrofit: Oakland City Hall

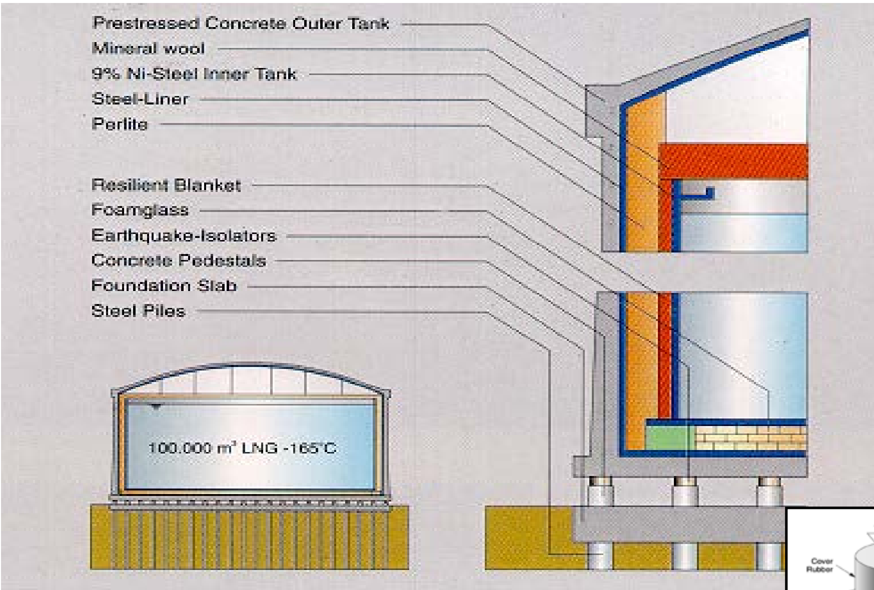


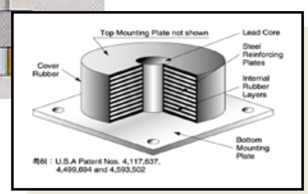
Fixed Base   Base Isolated

Gwangahn Bridge, Busan

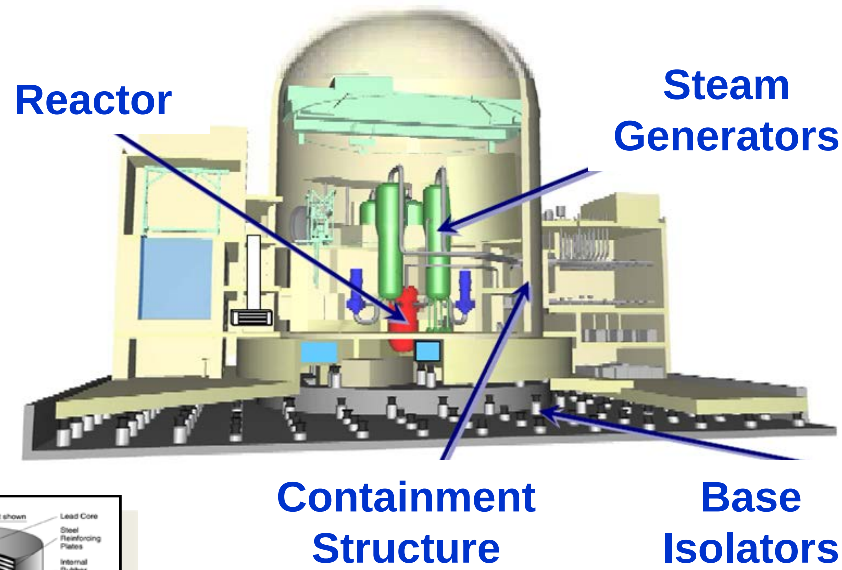
Base Isolated LNG Tank and Nuclear Power Plant

Based-isolated LNG Tank

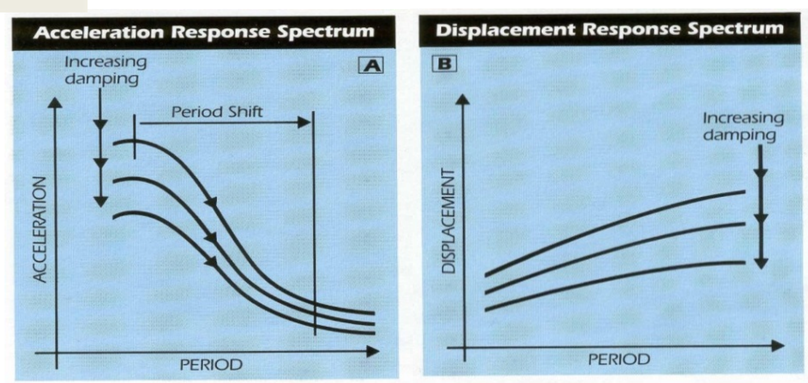




Base-isolated Nuclear Power Plant



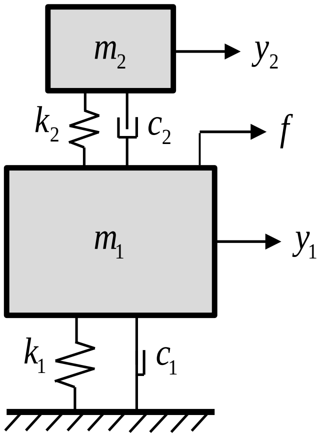
Design Response Spectra



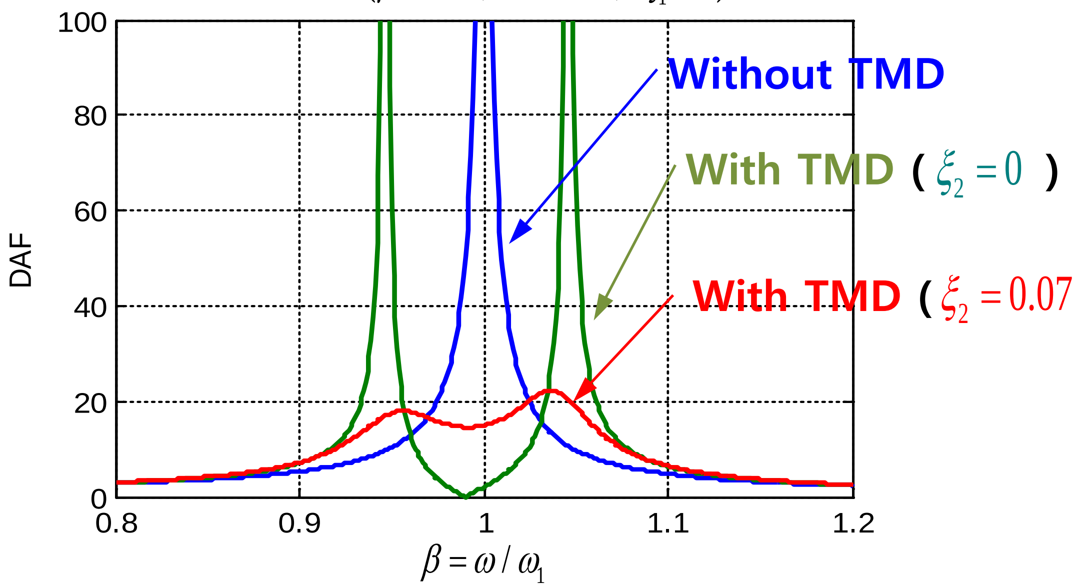
Tuned Mass Damper (TMD)

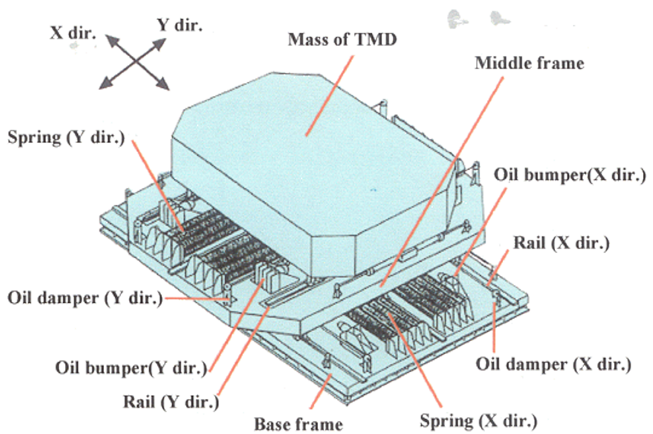
- **Dynamic Amplification Factor (DAF):**

$$\frac{y_{1,\max}}{\left|y_{1,stat}\right|_{\max}} = \frac{y_{1,\max}}{f_0 / k_1} = \sqrt{\frac{(\lambda^2 - \beta^2)^2 + N_1^2}{((\lambda^2-\beta^2)(1-\beta^2) - \lambda^2\beta^2\mu)^2 + M_1^2 + M_2^2 + M_3^2 - M_4^2}}$$

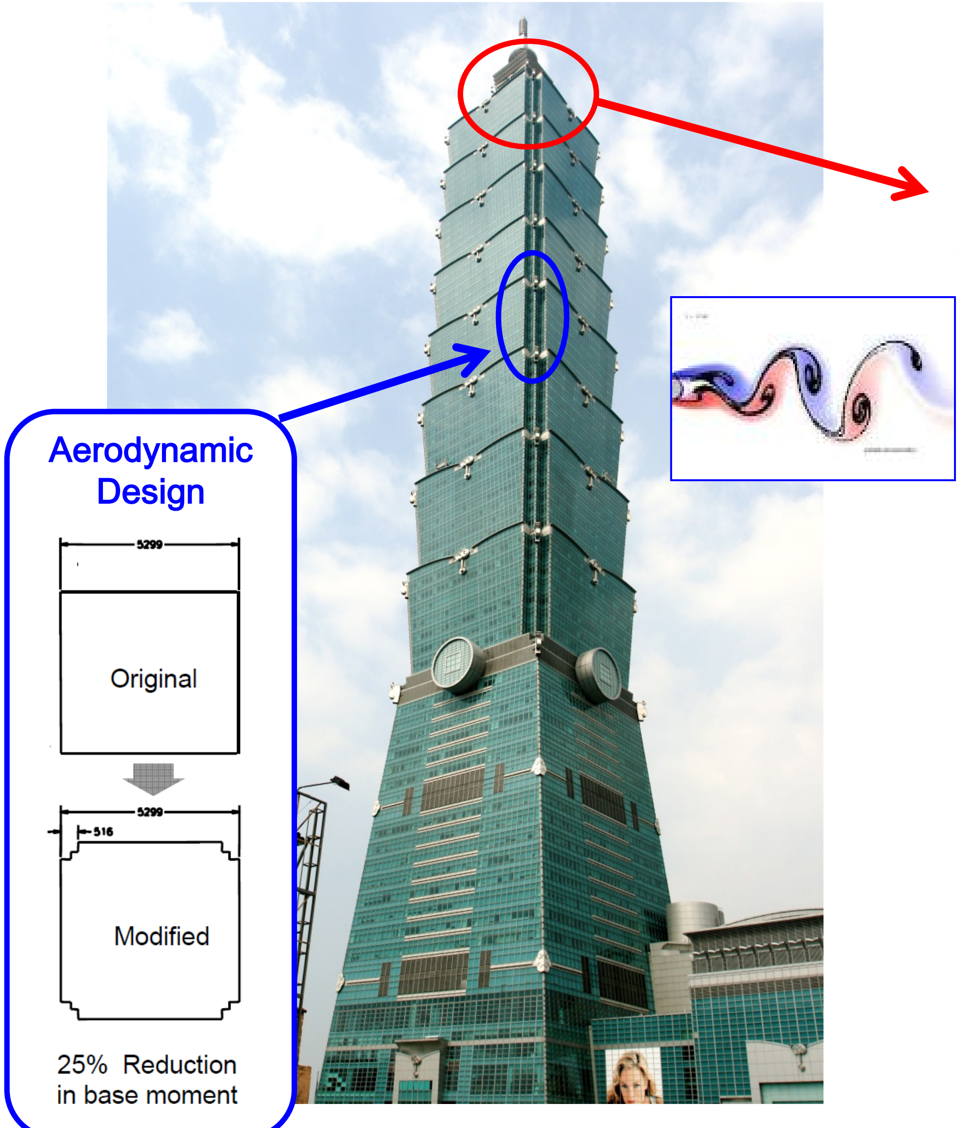


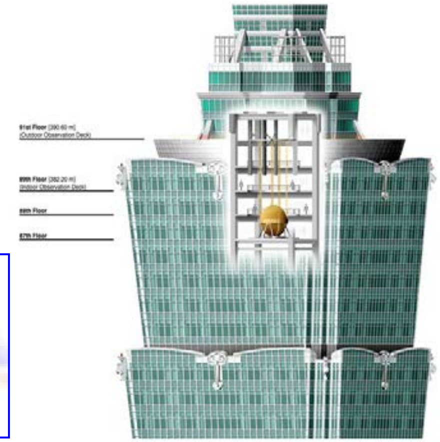
When $(\mu = 0.01,\ \lambda = 0.99,\ \xi_1 = 0)$





Taipei 101 Tower with TMD (Taipei)



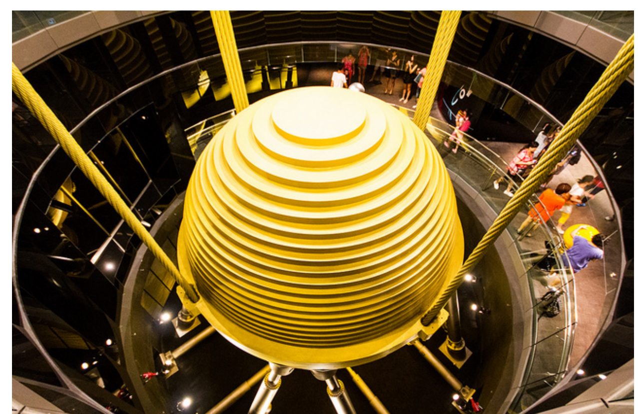


$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

$m = 660$ ton

$l =$ heights of 5 stories

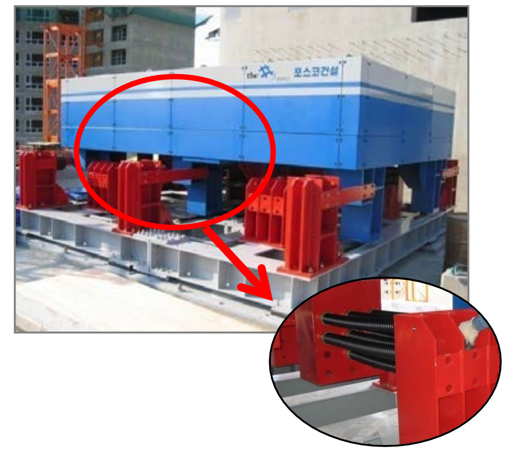
Pendulum Type TMD

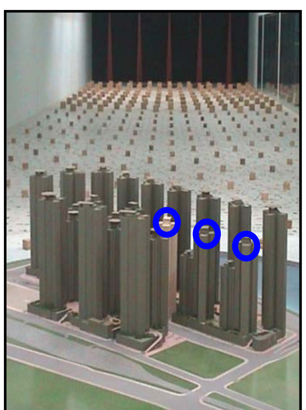


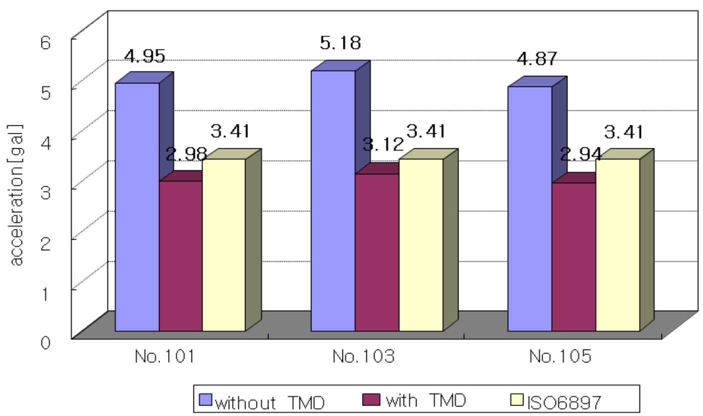
Condominium Buildings with TMD

Centum Park Apartments (Busan, Korea)

TMD Installed







Natural Frequency and Damping

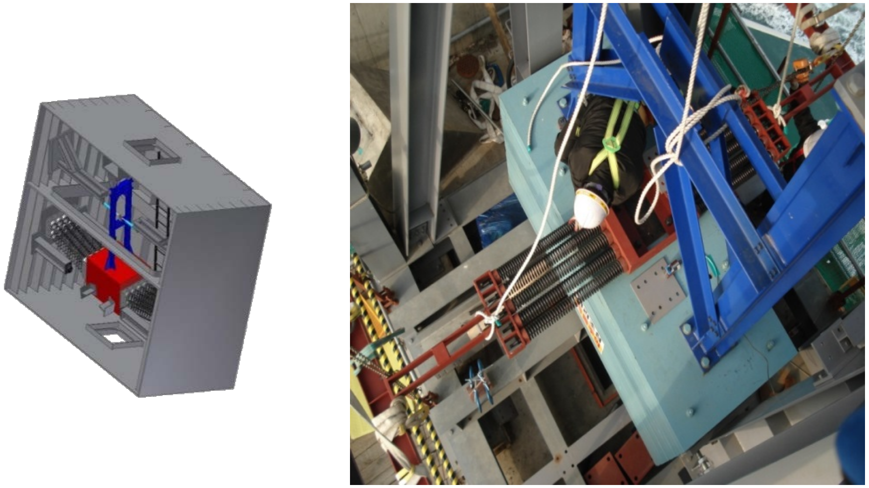
		Nat. Freq. (Hz)	Damping (%)
Building	Design	0.52	2.0
	Test	0.64	3.07
TMD	Design	0.52	6.0
	Test	0.54	11.7
	Reset	0.64	

(Courtesy of Y-S. Kim, TE Solution)

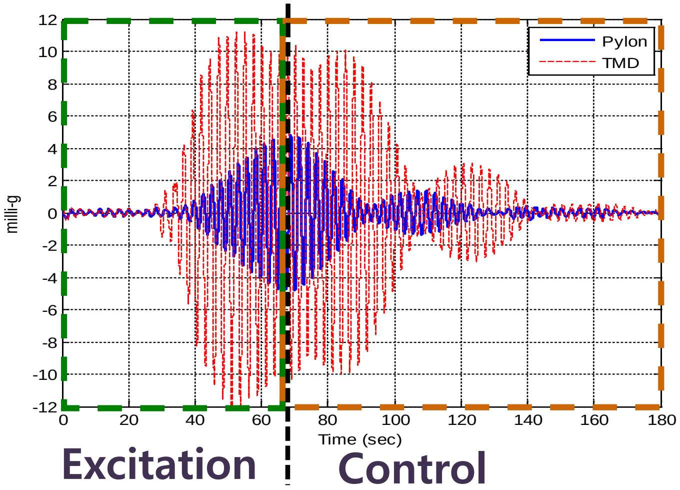
Pylons of Geoga Bridge with TMD

Geoga Cable-stayed Bridge

TMD Locations on Pylons



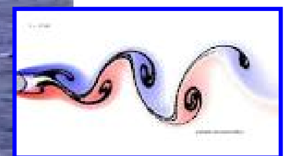
Pendulum-type TMD



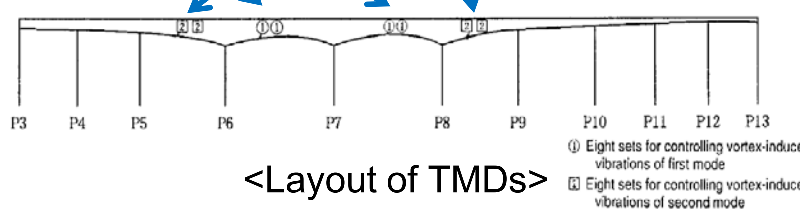
TMD Performance

(Courtesy of Y. Fujino, U. of Tokyo)

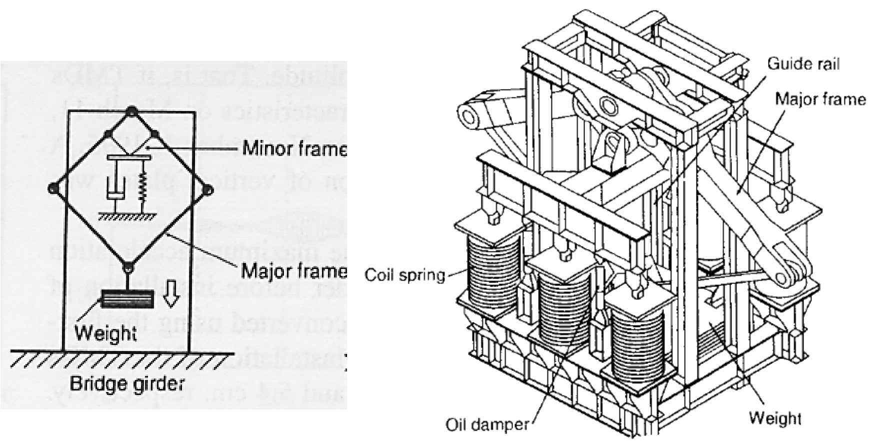
Multiple TMDs: Tokyo Bay Crossing Bridge



8 sets for 1st mode 8 sets for 2nd mode

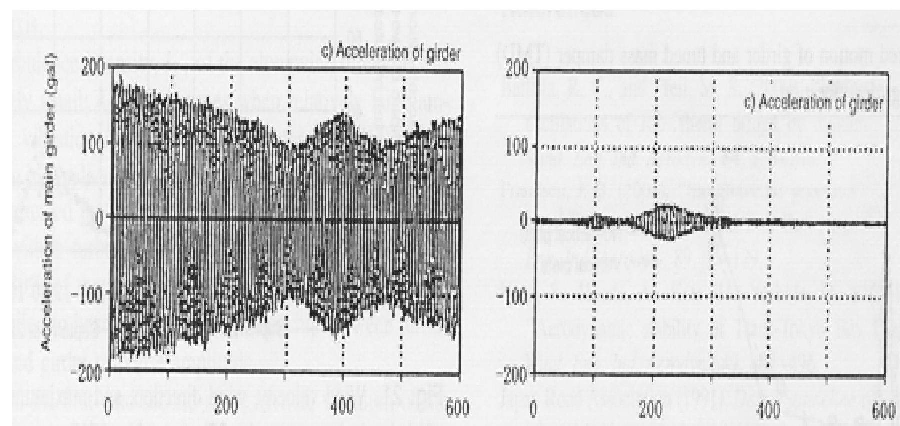


<Layout of TMDs>



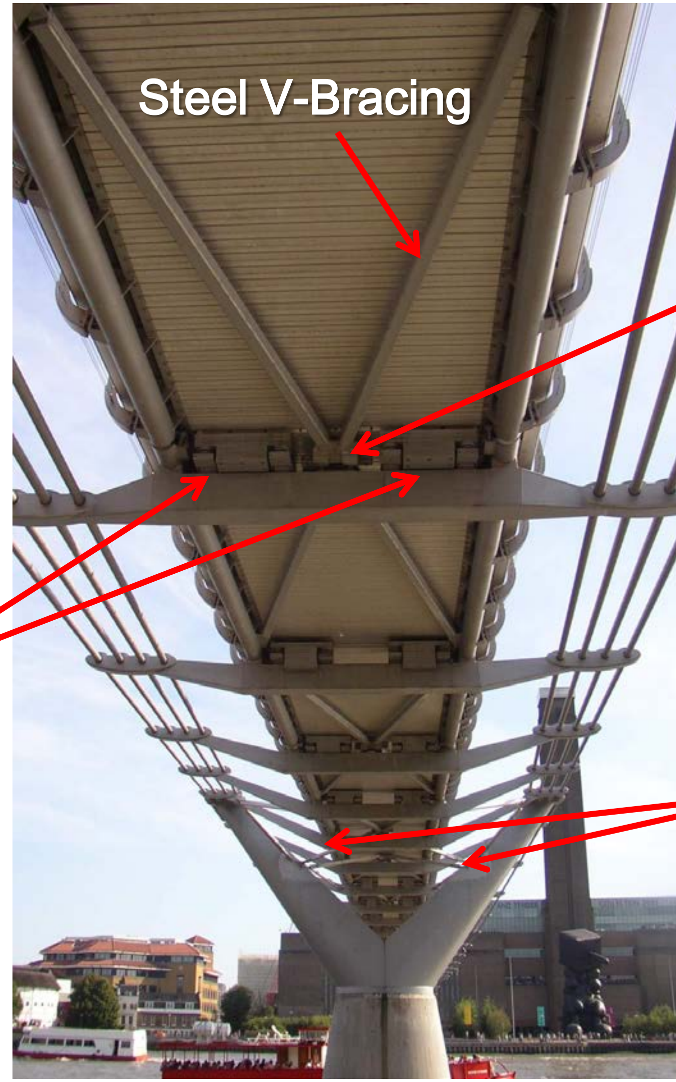
Installed TMD

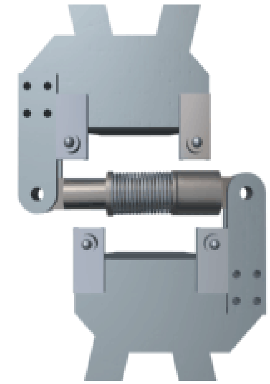
TMD Performance



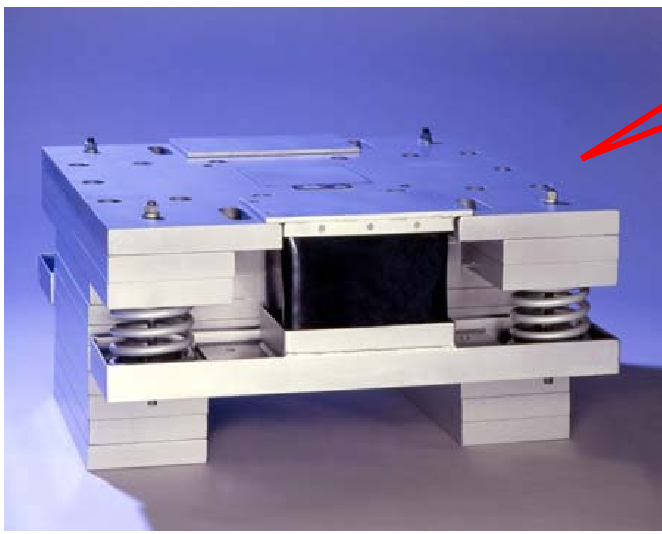
[w/o TMD] [w/ TMD]

TMDs & Dampers: London Millennium Bridge





Viscous Damper on V-Bracing



Tuned Mass Damper

Viscous Damper (Piers-Deck)

(Courtesy of SH. Lee & L. Chung, Dankook U.)

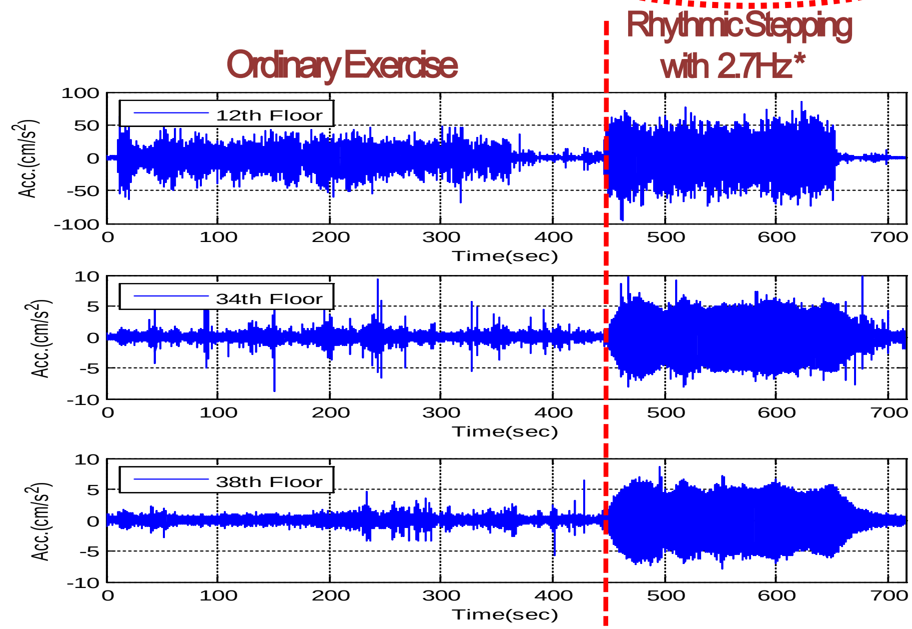
Aerobic Dancing Induced Vibration of Building

(Techno-mart Building, Seoul)

TMD+AMD

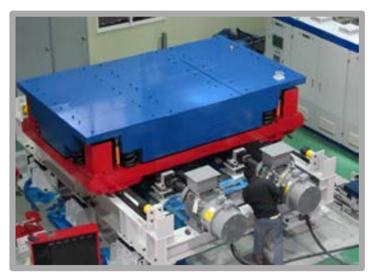
Wind Vibration Control

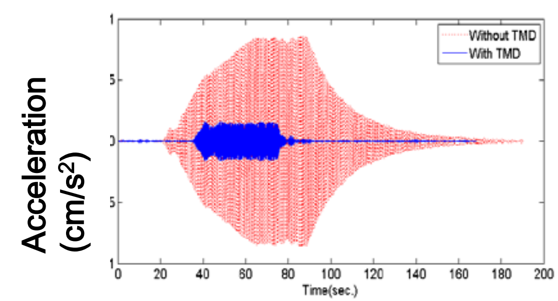
Vertical Acceleration (*Nat. Freq.=2.7Hz)



38th Fl. 12th Fl.

TMD & Vertical Acceleration

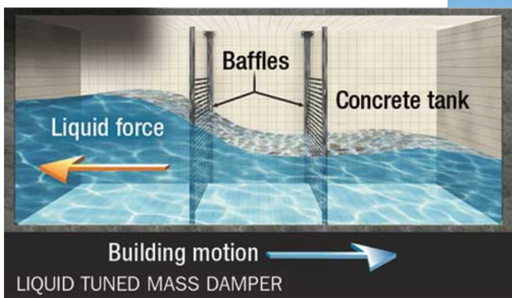




Tuned Liquid Mass Dampers (TLMD/TLCD)

One Rincon Hill South Tower (San Francisco)

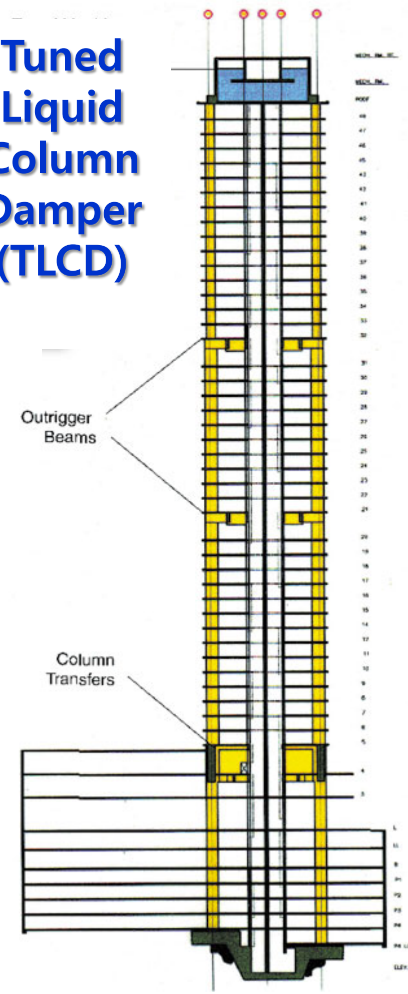
Slushing-type Damper (TLMD)



TLMD

One Wall Center (Vancouver)

Tuned Liquid Column Damper (TLCD)



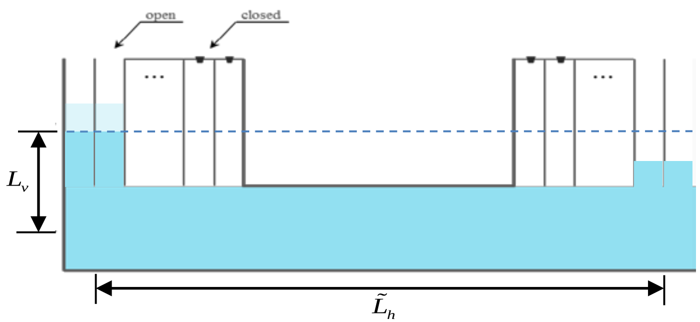
TLCD

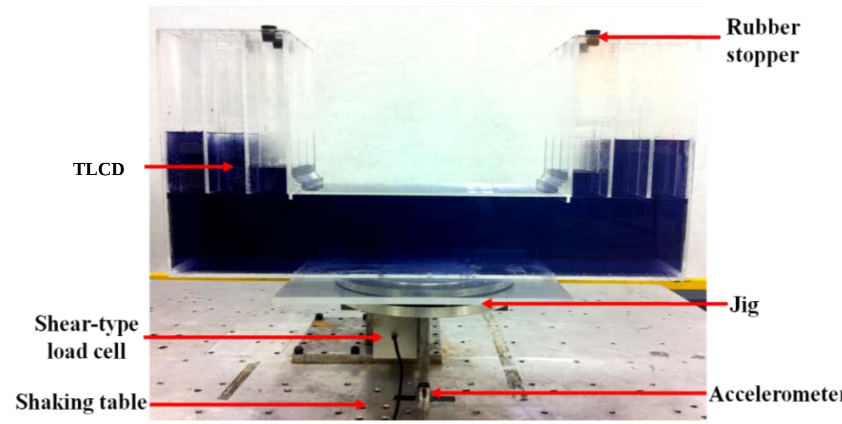
TLCD with Multi-cells

- **TLCD with multi-cells:**

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{(\frac{\nu}{2}\tilde{L}_h + 2L_v)}}$$

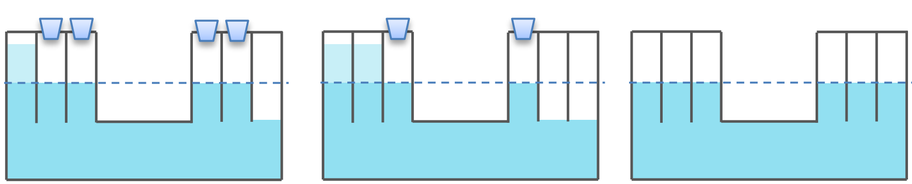
where $\tilde{L}_h = \frac{\bar{n}}{n}\nu[L_h + \left(\frac{L_c}{n}\right)(n-\bar{n})]$





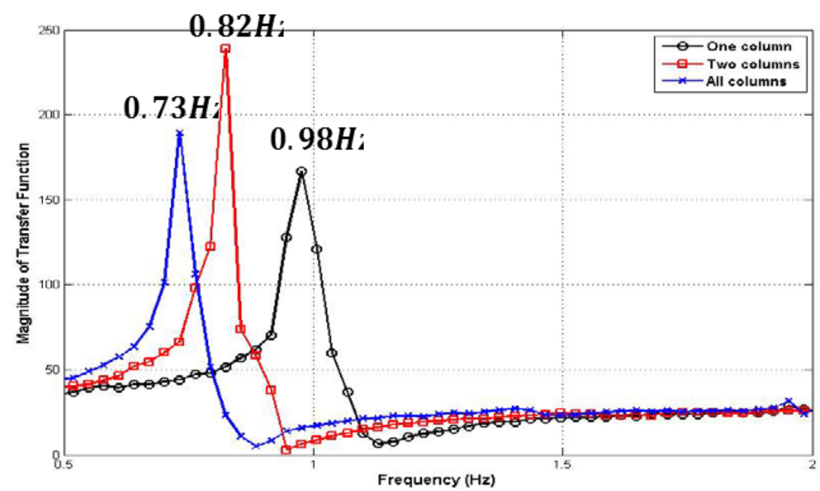
❖ ***Analytical Natural Frequencies***

1-column **2-columns** **3-columns**

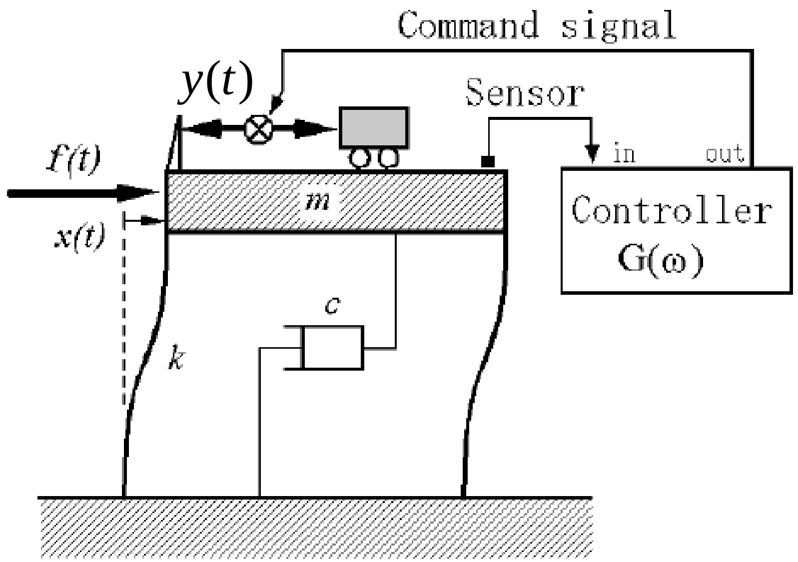


0.93Hz 0.78Hz 0.70Hz

Shaking Table Test: $|H(\omega)|$



Active Control: Closed-Loop

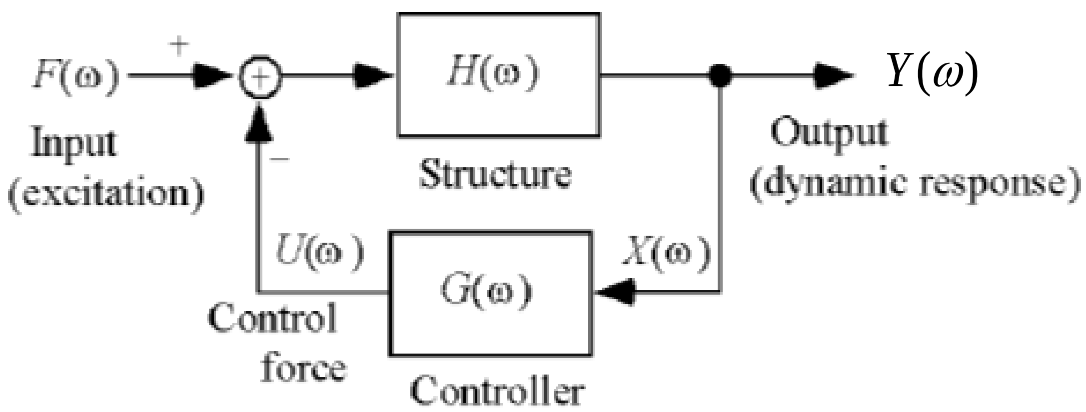


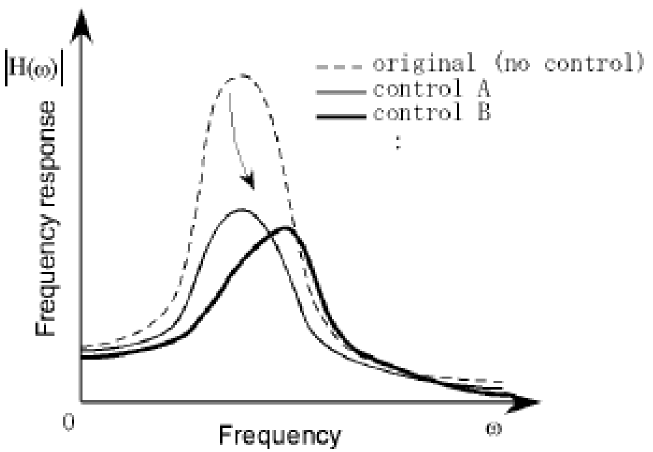
Without Control

$$Y(\omega) = H(\omega) F(\omega)$$

With Control

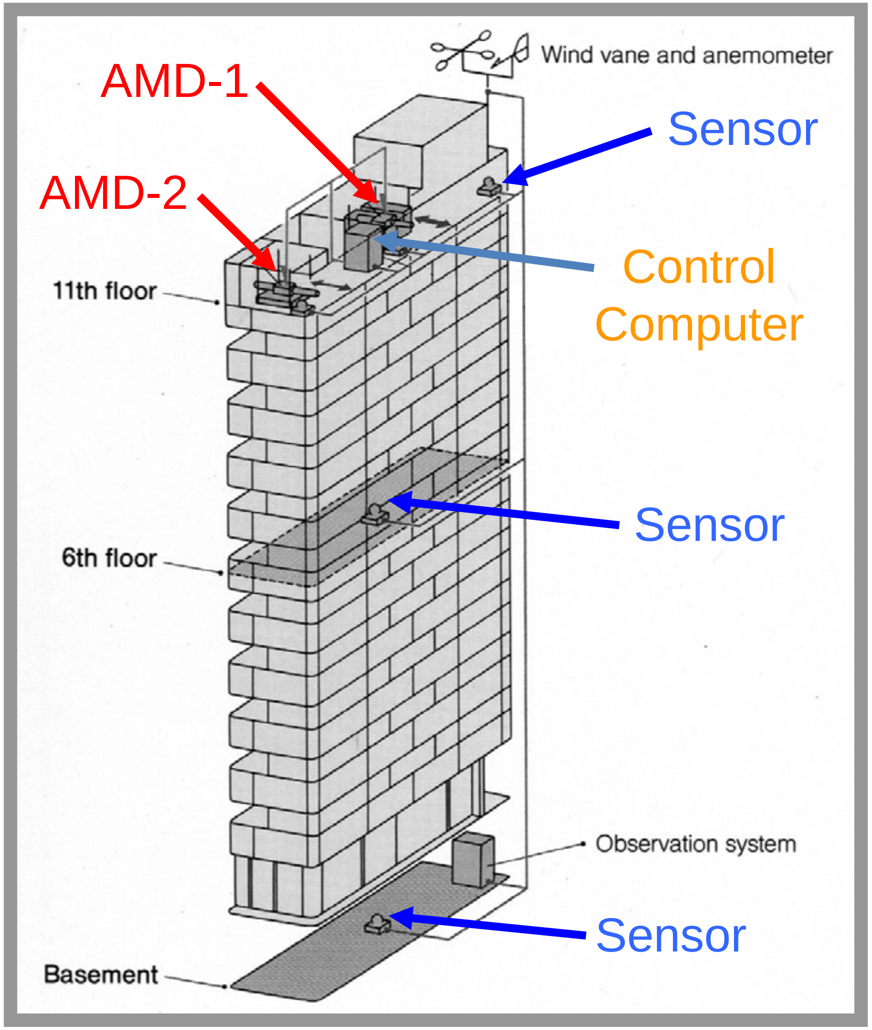
$$Y(\omega) = \frac{H(\omega)}{1 + H(\omega) G(\omega)} F(\omega)$$





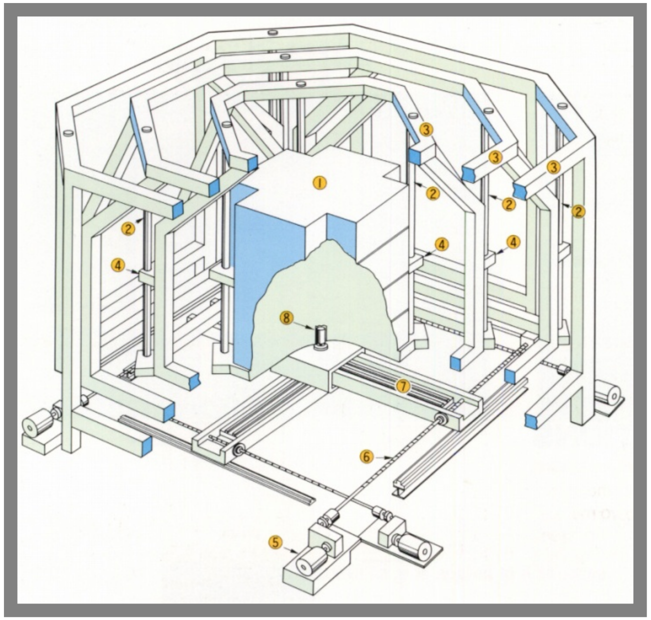
First Active Mass Damper on Building

Kyobashi Seiwa Building (1989)

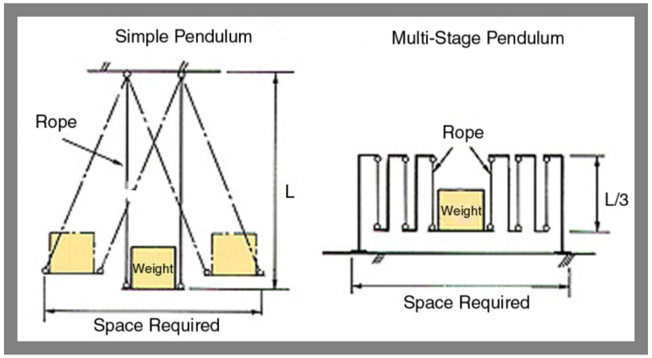


Hybrid Mass Damper on Building

Yokohama Landmark Tower (1993)



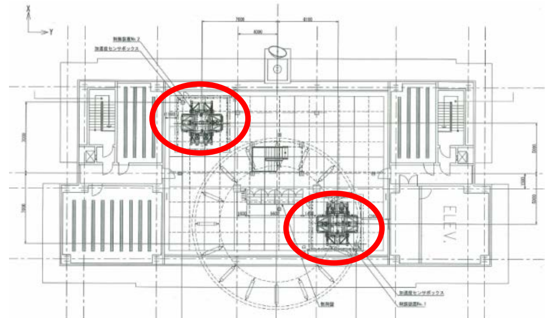
Multi-stage Pendulum



(Courtesy of JH Lee at Lotte E&C)

Active Mass Dampers (AMD) on Lotte Hotel

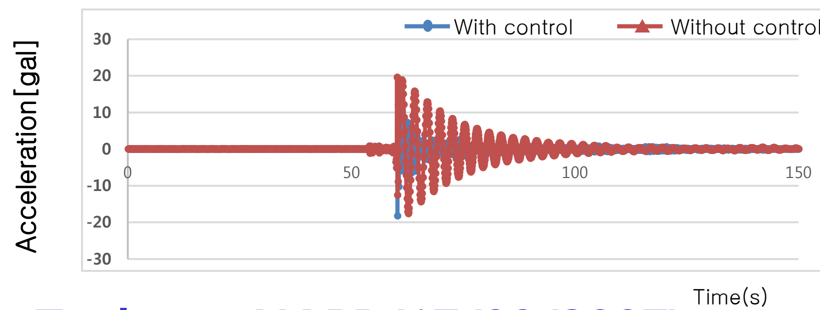
(Height: 110m with 24 Stories)



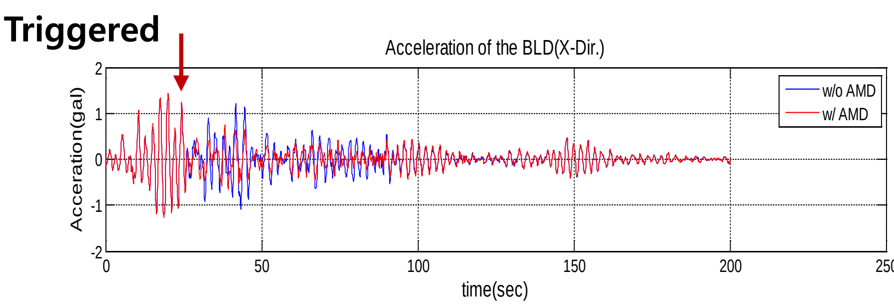
Top Floor w/ 2 AMDs

AMD: 2@26tons

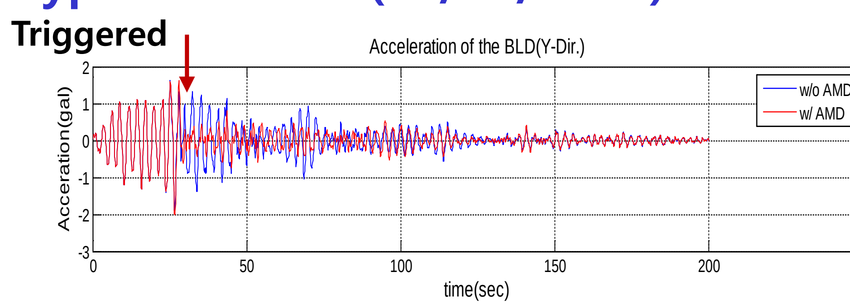
Free Vibration: Acceleration at Top



Performance during Typhoon NARI (17/09/2007)



Acceleration at Top (in X –dir.)



Acceleration at Top (in Y –dir.)

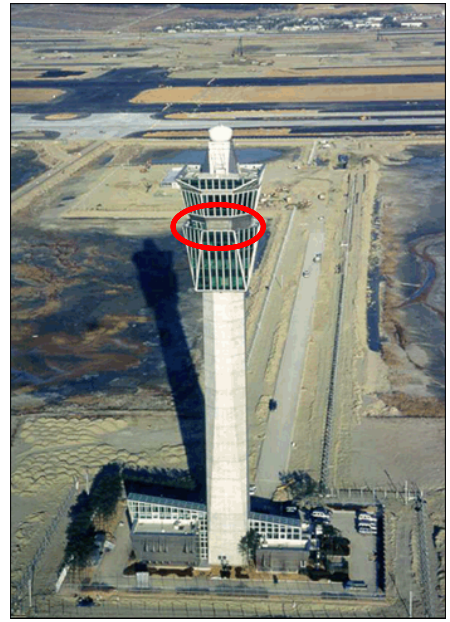
(Courtesy of H-M. Koh, Seoul Nat. U.)

Hybrid Mass Damper on Air-traffic Control Tower

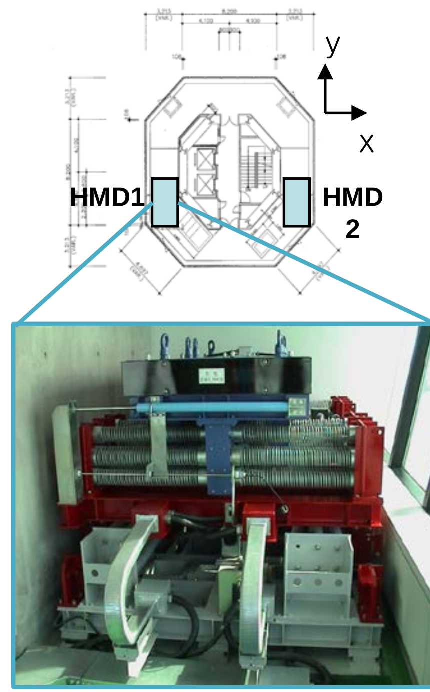
Incheon Airport Control Tower (2000)

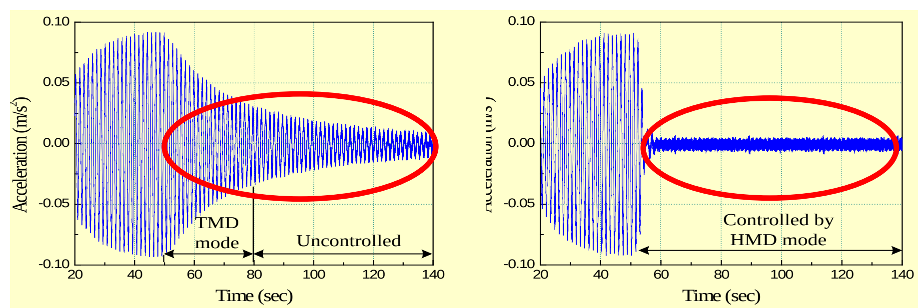
Items	Dynamic parameters (Tower)
Total Mass	6079 ton
Natural Freq.	X : 0.709Hz, Y : 0.737Hz
Damping Ratio	0. 6%

Items	Dynamic parameters (HMD)
Type	Hybrid Mass Damper (HMD)
Control Direction	X, Y - 2 direction
Moving Mass	X : 6.78 x 2 ton Y : 9.23 x 2 ton
Operation	Servo motor, LM guide
Control Algorithm	LQR + Gain scheduling
Max. Stroke	+/- 350 mm
Natural Freq.	X : 0.703Hz, Y : 0.726Hz
Optimal Damping Ratio	15 %
Placement	Control room (19th floor)



Air Traffic Control Tower: 100.4 m
Natural Frequency: 0.71 Hz

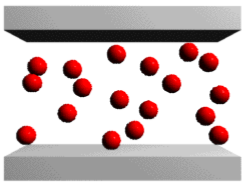


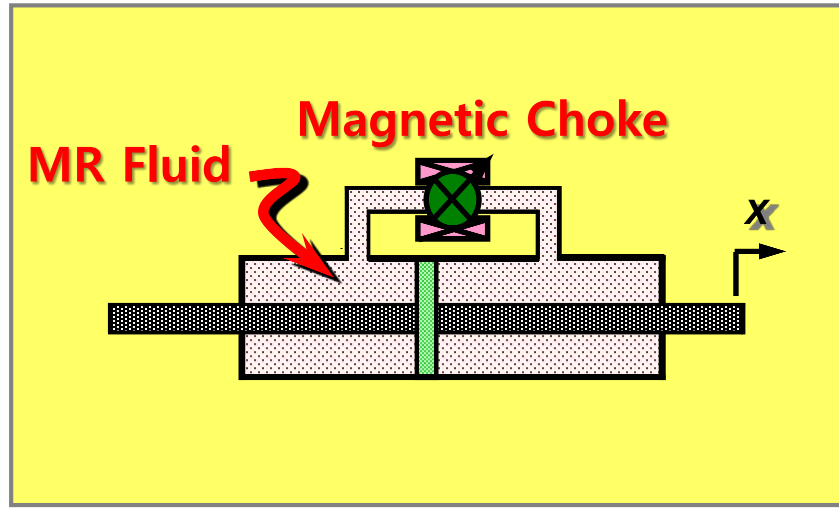


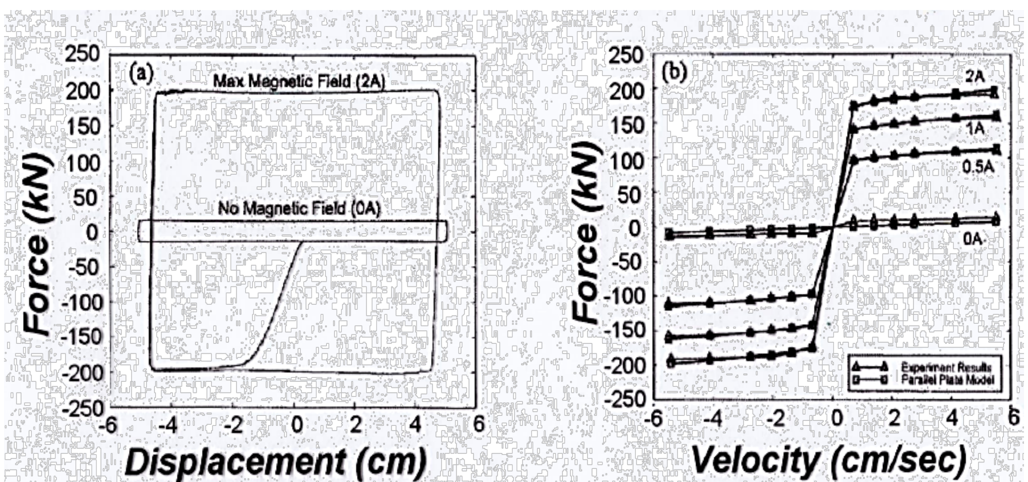
Signal w/o HMD **Signal w/ HMD**

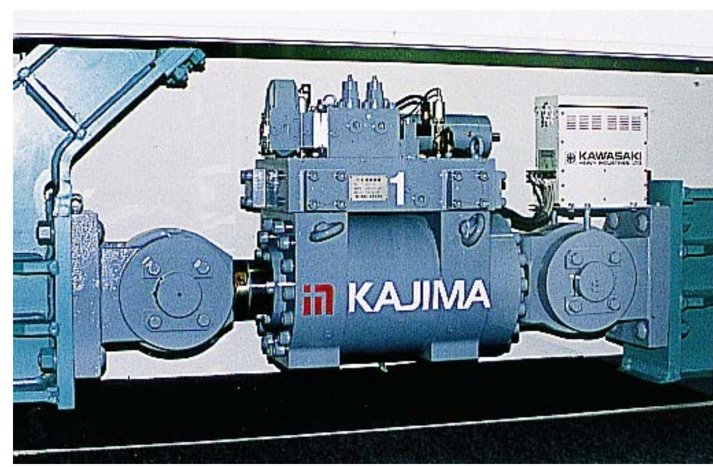
Magneto-rheological (MR) Damper

MR Fluids







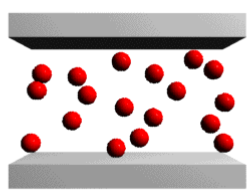


(Courtesy of B. F. Spencer, Jr., UIUC)

Semi-active Control Using MR Dampers

**National Museum, Japan:
MR dampers (30 ton)**

MR Fluids



**Wind Vibration Control of Stay-cables
(Dong-ting Bridge, China)**

ICT for Disaster Management



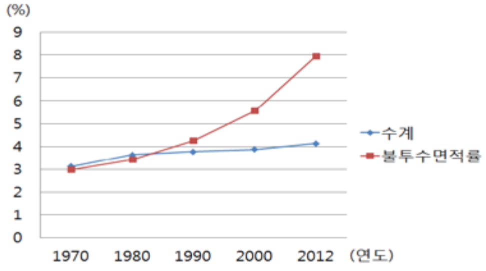



(Courtesy of DG. Yoon at Yonsei U.)

Increase of Disaster Risk Factor

Urbanization & Industrialization

- Change of social structure by urban- and industrialization
- High density, High-rise building:
  → Increase of impervious surface
- Concentration of population & becoming elderly society
- Complex disasters in urban: Large-scale damage



▲ Increase of impervious surface (National: 3%->7.9%), Ministry of Environment in Korea, 2013

Global Climate Change

- Average temperature increases 0.6-0.74℃ in the last 100 years in the World.
- At the end of 21st century, average temperature may increase 3.7℃, and mean water level may increase 63cm in the World.
- Due to climate change, natural disaster is becoming larger and more complex.

Disasters Related to Global Warming

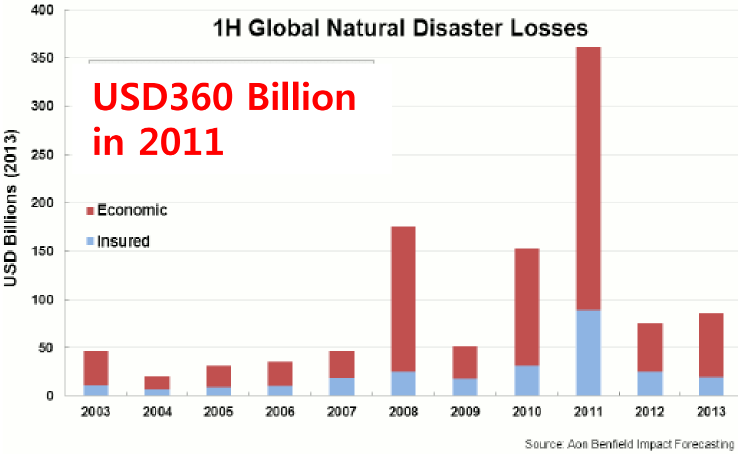
❖ **Natural Disaster has drastically increased worldwide due to Global Warming.**
USD50 Billion/year in 1980's → USD200 Billion/year in 2000's.

Hurricane Katrina, US (2005)
Casualty: 2,541명, Damage: USD100 Billion

Flood in Queensland, Australia (2010)
Casualty: 35명, Damage: USD0.8 Billion

Typhoon Haiyen, Philippines (2013)
Casualty: 2,400, Damage: USD14 Billion

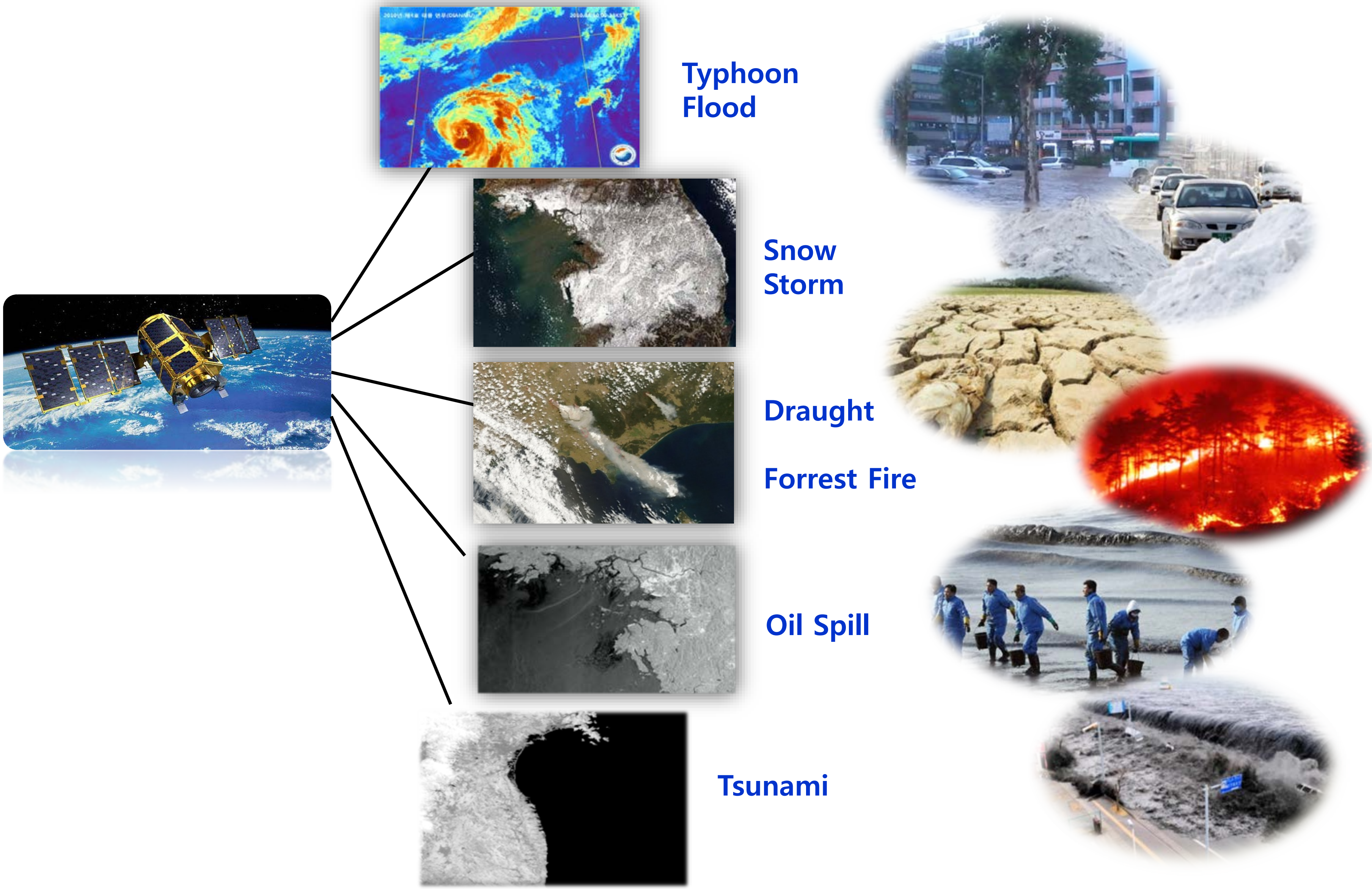
Tornados, US (2011)
Casualty: 550, Damage: USD7.5 Billion



Hurricane Irene, US (2011)
Evacuation: 2.5 million people
in 12 States along the East Coast

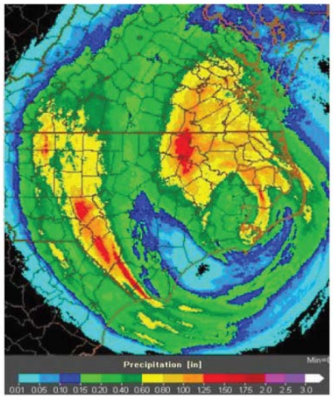
(Courtesy of MI. Lee at UNIST)

Disaster Monitoring Using Remote Sensing

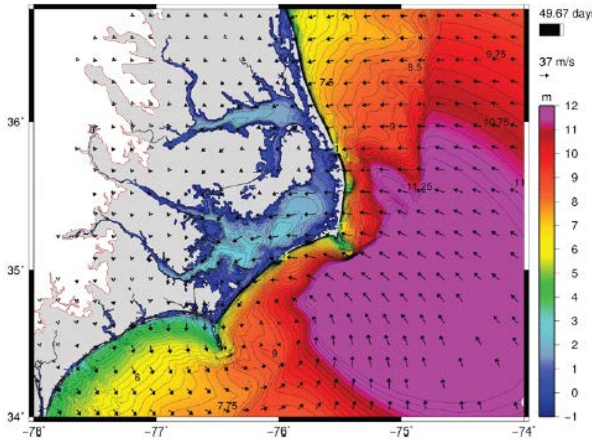


(Courtesy of MI. Lee at UNIST)

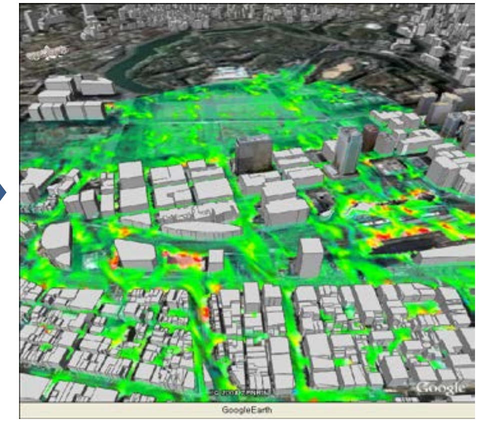
Disaster Modeling/Prediction Using Super-computing



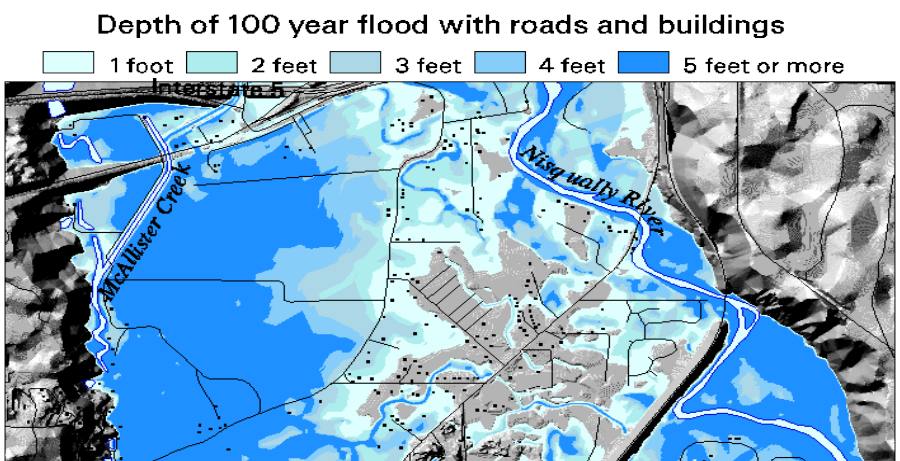
Meteorological Monitoring System



Local Meteorological Hazard Prediction System

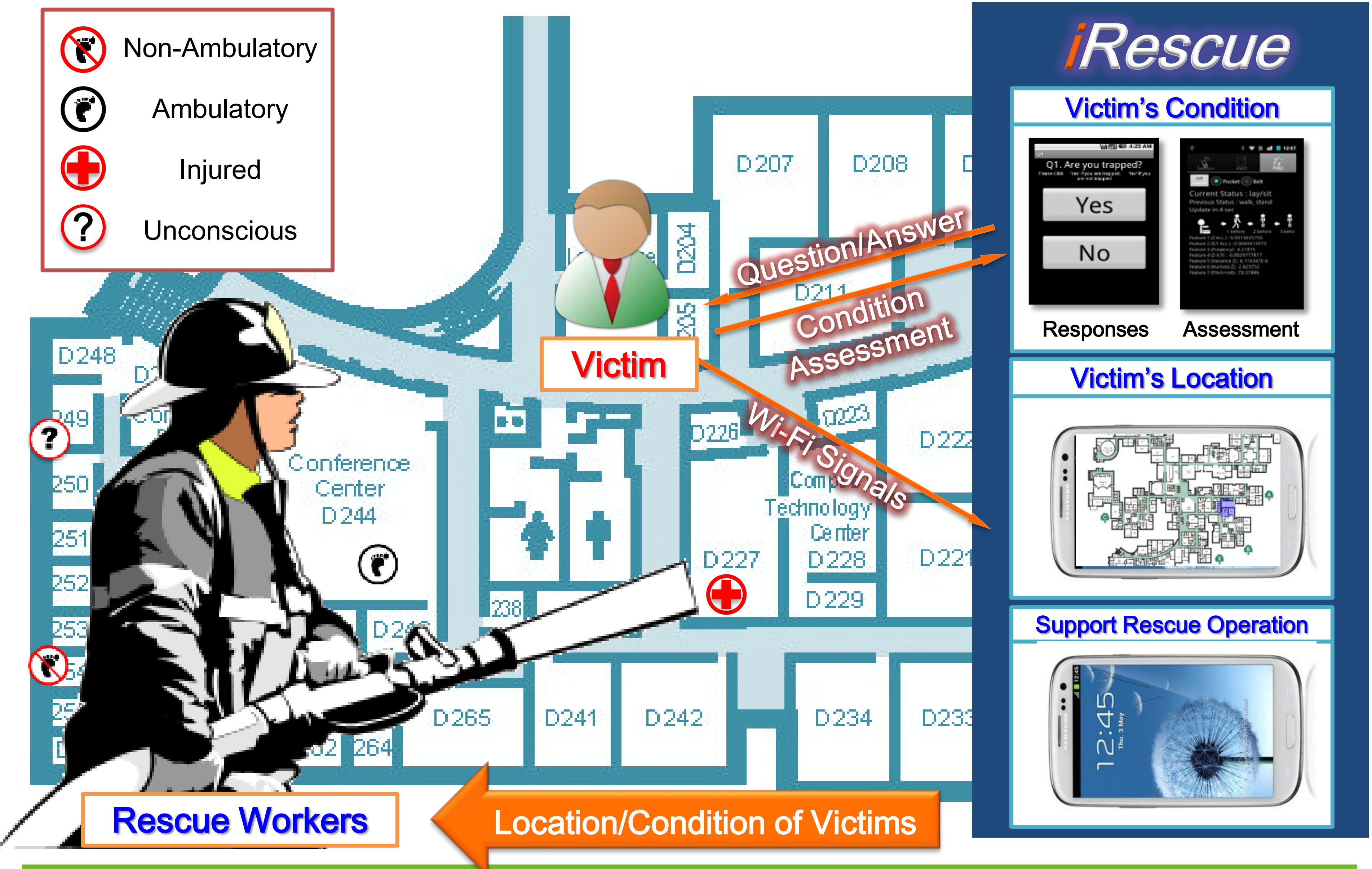


Urban Strom/Flood Disaster Prediction System



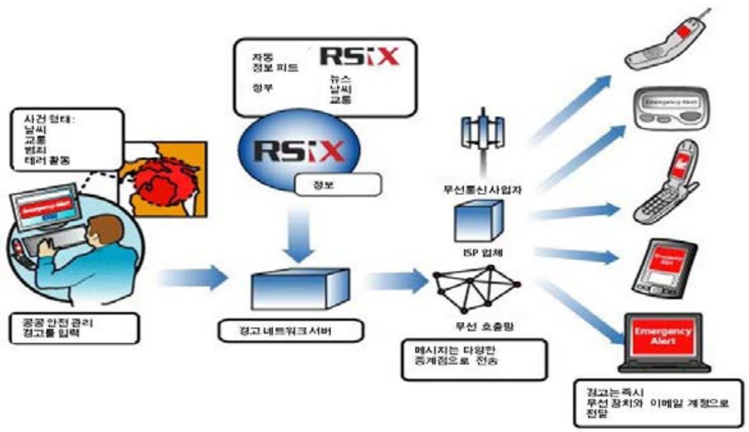
GIS-based Flood Damage Prediction & Vulnerability Analysis

Smart Phone-based Rescue Supporting System



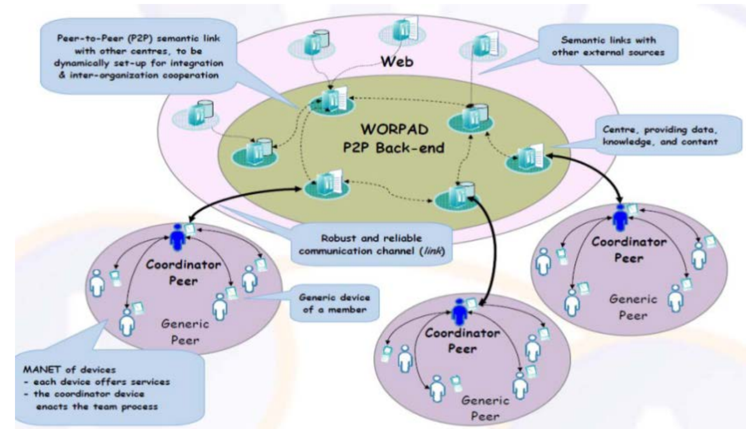
(Courtesy of SJ. Cho at U. of Seoul)

ICT-based Rescue Supporting Systems



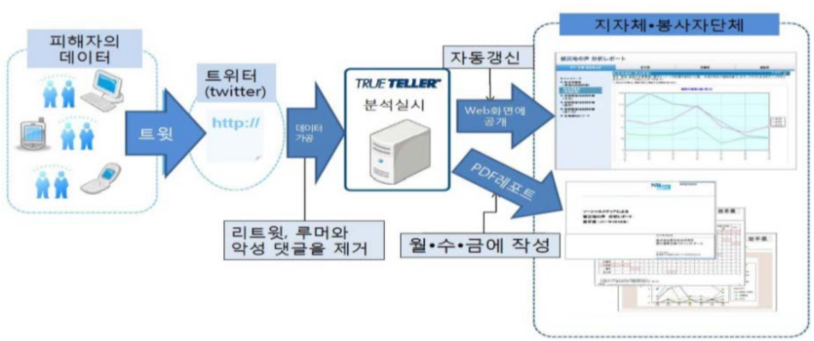
ReadyNotifyPA: Philadelphia

Automatic Disaster Alarming & Information Sharing



Smart WorkPAD: EU

Smart Phone-based Rescue Information Sharing



Victim's Voice Recognition System: Japan

SNS-based Disaster/Victim Information Recognition & Sharing

Emergency 2.0 Australia:

SNS-based Disaster Information Sharing between Local-Central Governments

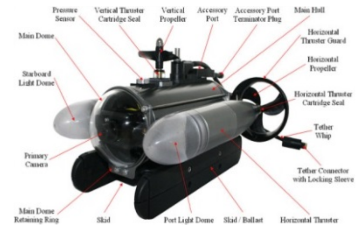
(Courtesy of H. Myung at KAIST)

Robotics for Disaster Rescue Operations

Pioneer
(Chernovile)

I-Robot
(Fukushima)

Queens
(Fukushima)



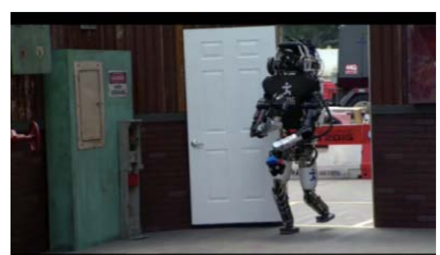
VideoRay
(Ship Sunken)

Crabstar
(Ship Sunken)

Performance was Not Satisfactory under Harsh Environments!!!

DARPA Robotics Challenge (2013-2015)

1. Drive Vehicle under Disaster Condition
2. Move through Debris
3. Remove Obstacles
4. Open Doors & Enter Rooms
5. Climb up Stairs & Walk on Catwalks
6. Use Tools for Breaking Concrete Walls
7. Locate and Close Leaking Valves
8. Connect Fire Hose and Open Valves



Multiple Robot Operation

- **Multiple Robot Operation**
  - Construction of Map and Recognize Condition Using Multiple Robots in Disaster Areas Un-accessible to GPS.
  - **Technologies:**
    - Recognition of Environment and Locating other Robots
    - Communication with other Robots
    - Move through Obstacles and Work in Collaboration with Others

(Courtesy of M. Shinozuka)

Resilience Analysis for Bridge Retrofit

Retrofit by Steel-Jacketing of Columns

Scenario Earthquakes

↓

Ground Motion Intensity at Bridge Sites (PGA, PGV)

↓

Bridge Fragility (not Retrofitted)

Bridge Fragility (Retrofitted)

↓

Remaining Traffic Capacity of Damaged Highway Network

↓

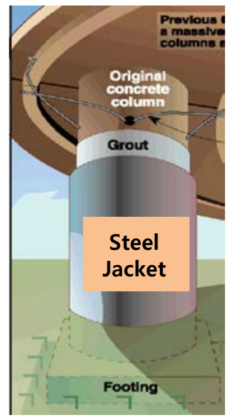
Traffic Flow Analysis

↓

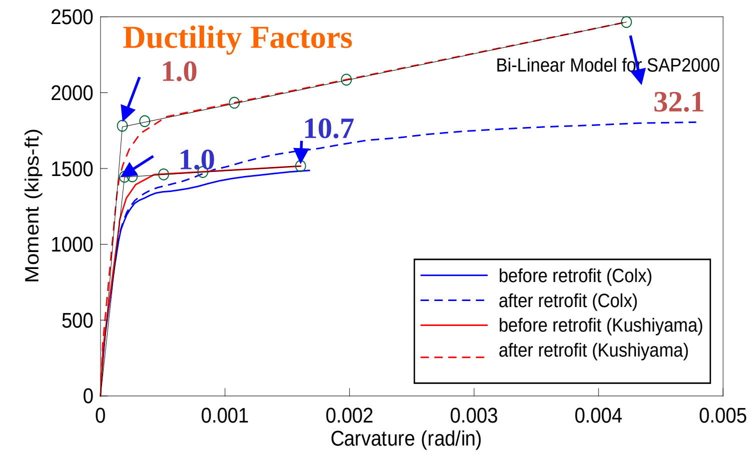
Drivers' Delay & Opportunity Loss

↓

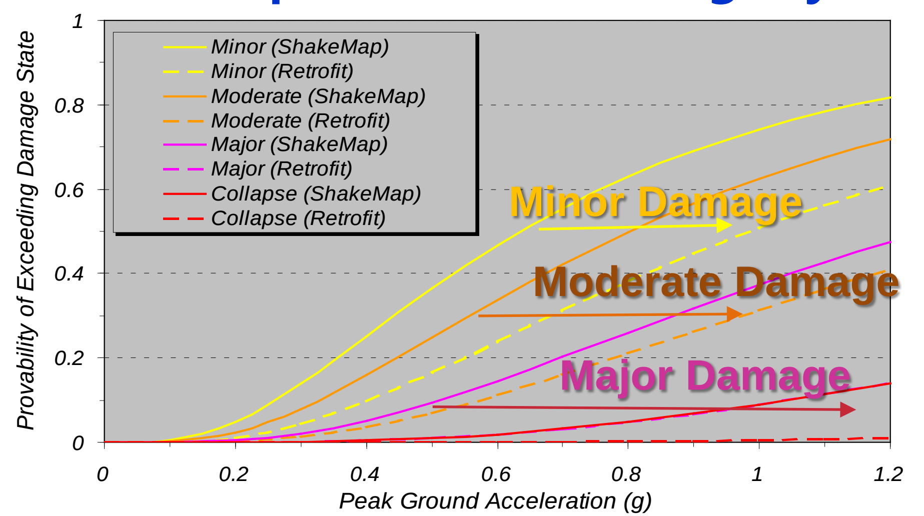
Economic Analysis & Benefit Cost Ratio



Improvement in Column Ductility



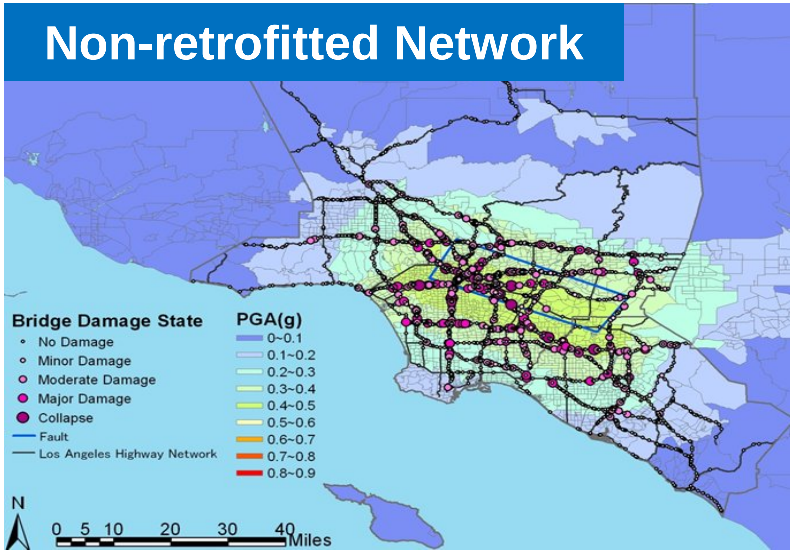
Improvement in Fragility

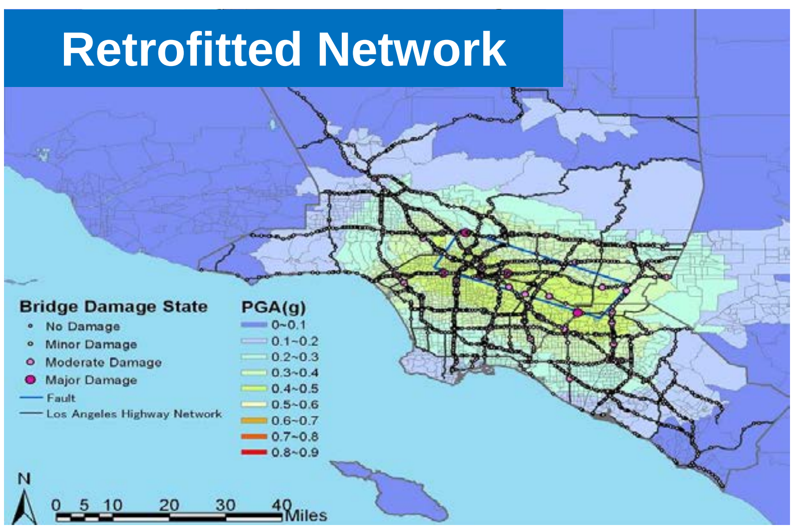


(Courtesy of M. Shinozuka)

Bridge Condition and Social Cost Analysis

Bridge Condition

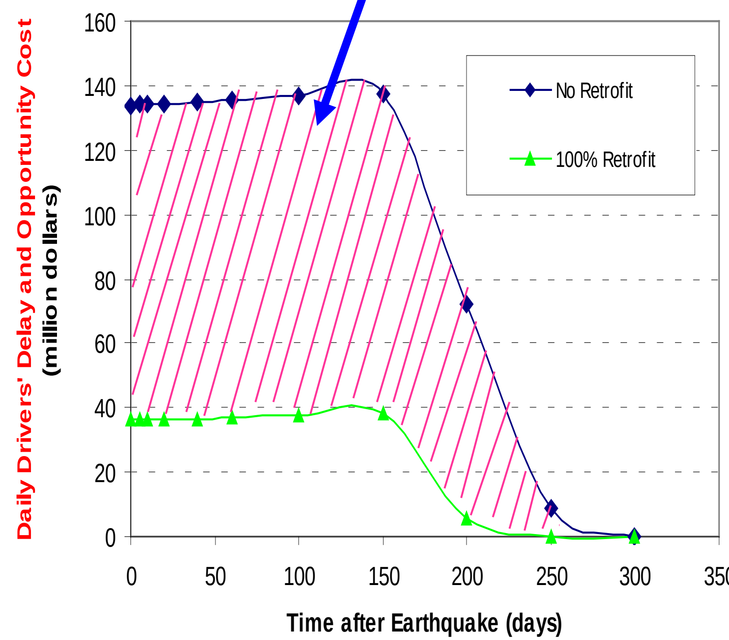




Social Cost Analysis

(Over the restoration period: 10 Months)

Social Cost Avoided = Shaded Area
(Drivers' Delay Cost)



Social cost: average hourly wages
(~$21.77/h for Los Angeles in 2005)

Problems in Disaster Management

1. Emphasis mainly on the Post-disaster Response/Recovery:
   - Low Priority on Disaster Prevention and Preparedness
   - Higher Priority on Cost/Benefit than Safety

2. Unsystematic Disaster Management Systems:
   - Lack of Systematic Analysis of Causes
   - Lack of Coordination in Policies, Laws, & Regulation
   - Need Integrated National Disaster Management Systems

3. Lack of Cooperation among Agencies:
   - Among Central/Local Agencies and Public/Private Organizations
   - Need a Commanding Officer on Rescue Operations at Site

4. Lack of Disaster Management Experts
   - No Formal Education Programs on Disaster Management
   - Multi-disciplinary Expertise/Experience are Required.

5. Need Advanced/Practical Technology for Disaster Management
   - Emerging ICT including Smart Structure Technology
   - Socio-economic Aspects are to be Incorporated.

International Collaborations on R&D and Education

International R&D Consortium : *KKHTCNN*

Symposium on Civil Engineering among

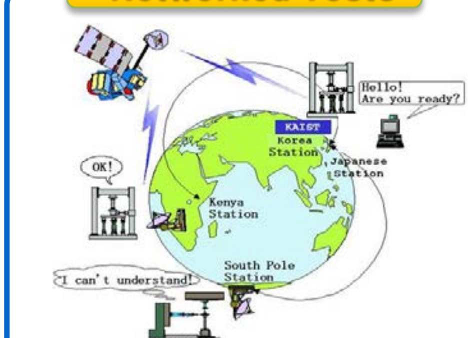
Kyoto University (Japan)
KAIST(Korea)
Hong Kong University of Science & Technology (China)
Tongji University (China)
Chulalongkorn University (Thailand)
National Taiwan University (Taiwan)
National University of Singapore (Singapore)

- ✓ **Collaborations in researches & education in the East Asia**
- ✓ **The 1st Symposium began between Kyoto University and KAIST in 1988.**
- ✓ **The 29th Symposium will be held at NUS in 2016.**
- ✓ **Many joint researches have been carried out among the KKHTCNN members.**

Panel Discussions

Annual Symposium

Networked Tests



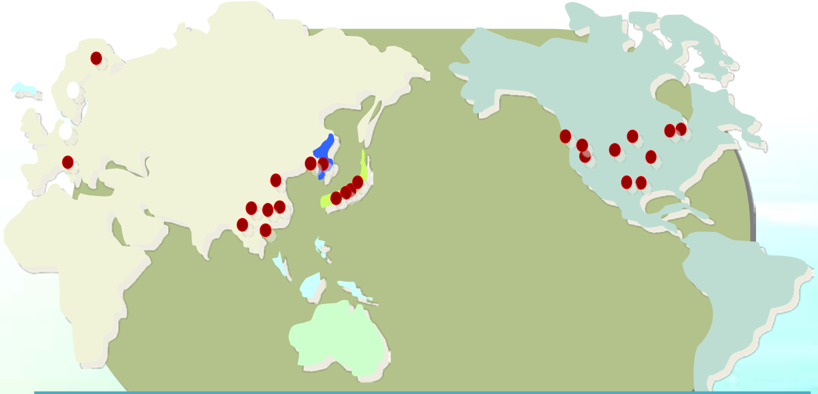
International R&D Consortium: ANCRiSST

Asia-Pacific Network of Centers for Research in Smart Structures Technology

(ANCRiSST: http://ancrisst.kaist.ac.kr, since 2003)

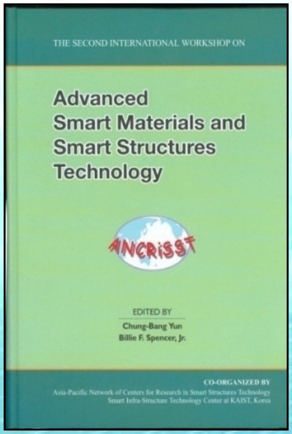
A center-based consortium on smart structures technology in the Asian-Pacific region

- ✓ To develop synergies through joint research projects
- ✓ To better educate the next generation with smart structures technology
- ✓ To promote R&D on smart structure technology by international events

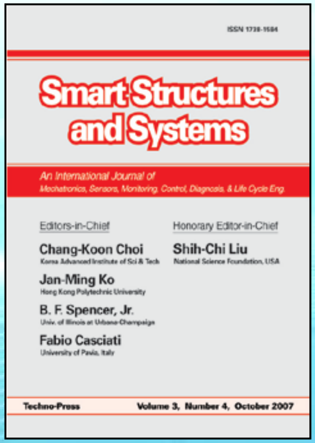


Currently 24 member institutions from Korea, the US, China, Japan, and Europe

Annual Workshops
(since 2004)



Official Journal
(since 2005)



Joint R&D
(2008-2012)

Asia-Pacific-European Summer School (AEPSS) on Smart Structure Technology

Goals of APESS Program

- To enhance students' understanding of the cross-disciplinary technological developments on the emerging subjects of smart structure technologies
- To develop the cross-cultural human-network and understanding for the future cooperation in their professional career development.
- 3 weeks' programs among the USA, Korea, Japan, China, India, Taiwan, & the UK since 2008. Next APESS will be held in Japan (2017) & China (2018).

Concluding Remarks






Concluding Remarks

- **Smart Structure Technologies** have been discussed regarding to Safety, Serviceability, & Resilience of Urban Infrastructure.

- **Multi-disciplinary Cooperation among Technologies and Social Sciences and International Collaborations are needed.**

- **Smart Structure Technologies** are expected to lead the technological developments to build **Resilient and Sustainable Urban Infrastructure** in the future.

Smart Structure Technology for

Safe-Resilient-Sustainable Society with Better Quality of Life!

Thank You for Your Kind Invitation and Attention!!

My Best Wishes for Your Great Professional Career!!

Acknowledgements:

Sincere Thanks to the Research Supports from KAIST & UNIST, and to the Great Contributions by Many Colleagues to this Lecture.