Membership Notes, October 2012

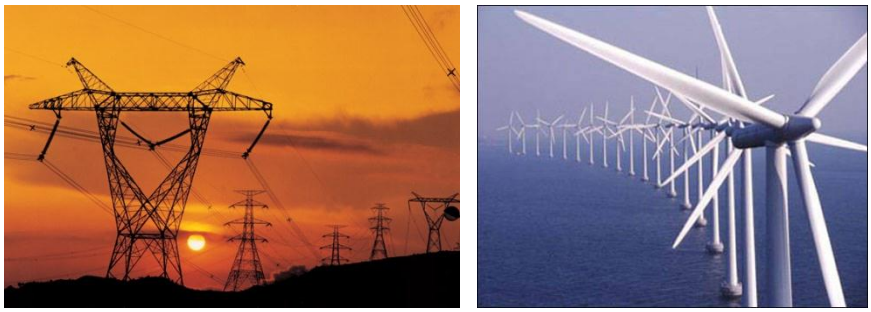
Vice President Ou's Letter Extended with Additional Graphics

We are pleased to offer an extended version of Dr. Ou's letter with the additional graphic that the staff of *Membership Notes* felt could not be adequately reproduced otherwise.

Dear Members and Colleagues,

I am pleased to introduce myself to you as the ISHMII Vice President for Member education and to write this issue of *Membership Notes* sharing my views on life-cycle performance monitoring, evaluation and design of civil infrastructure. I am a professor of civil engineering and engineering mechanics at Dalian University of Technology (DUT) and Harbin Institute of Technology (HIT), China.

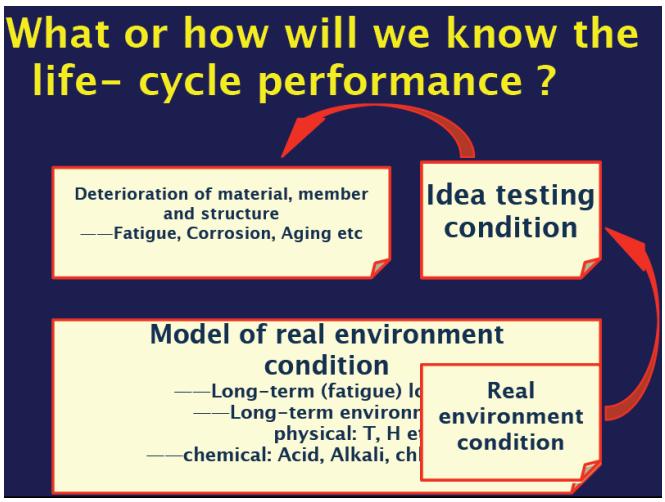
Background As you know, there is the largest scale infrastructure in the world to have been building in China in recent two decades, including transportation infrastructure (bridges, tunnels, highway, railway), buildings (tall buildings, spatial structures), hydraulic project (dam, wharf), offshore engineering (offshore platforms, offshore wind energy systems, pipelines), nuclear power plants and electric power transmission systems. Among them, six of highest tall buildings over the world are located in China, seven of longest span cable-stayed bridges in China, three of longest suspension bridges also in China; the Three Gorge Project of China is the largest hydraulic project around the world, and the highest dam (Jinping with a height of 305m) also in China.



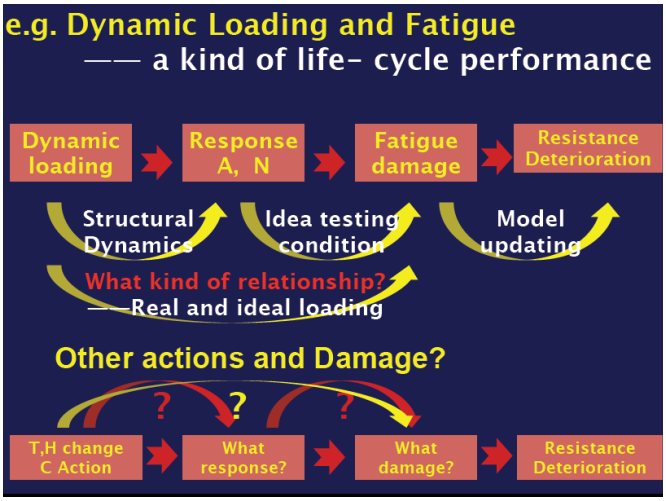
Large infrastructure in China

The life of civil infrastructure may be 50 years, 100 years or even longer. Unfortunately, civil infrastructure may be subjected to extreme environmental actions (e.g. earthquake, tsunami, hurricane, wave, current, ice, flood and rain or their combination actions), and sustaining harsh environmental actions or loads during their life-cycle service period. The extreme environmental actions may result in dramatic vibration, landslide or other natural disasters. While, the sustaining harsh environmental actions or loads may result in fatigue accumulative damage, steel corrosion, material ageing, as a consequence, the resistance capability of the structure will deteriorate. It needs us to understand the life-cycle performance and behavior of infrastructure for ensuring safety, serviceability, durability and sustainability of complicated large infrastructure during entire service life. The question is how much we know the life-cycle performance, how well we could predict the life-cycle performance, furthermore, how will we sustain the life-cycle performance of infrastructure? Very less knowledge and practice for answering above questions at current stage, in particular for the complicated large infrastructure! From another view of point, these challenge issues provide us the chance to develop approaches and technology of the life-cycle performance monitoring, evaluation, control and design of infrastructure.

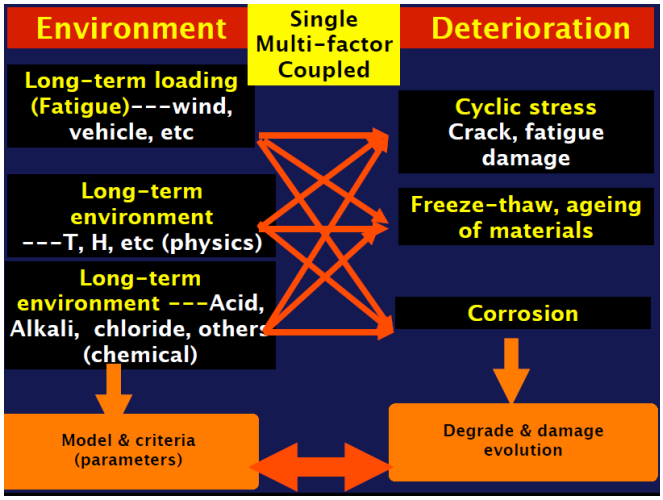
Traditionally, the small scale model test or accelerated test (force loading, environmental action or their combination) is frequently employed to investigate the behavior and life-cycle performance of materials, elements and even an entire structure, such as shaking table test, pseudo-dynamic test, hybrid simulation, wind tunnel test, fatigue test and durability test (corrosion test, freeze-thaw cyclic test, chloride permeability, etc.). The advantage of this kind of ideal testing conditions is that the unique mapping relationship between applied loads and corresponding response of a structure can be obtained and then the behavior and deterioration of structure can be further derived. For example, fatigue test of an element can be conducted to obtain the relationship between cyclic load range and structural response (e.g. stress), and then the deterioration in resistance of the element can be derived based on the fatigue accumulative damage; durability test can be performed accelerated to obtain the relationship between the corrosion rate and extent of rebar or steel elements with the chloride solution and then the deterioration in resistance of the element can be obtained. However, one of the disadvantages of this kind of ideal testing conditions is that the effect of a single action on a structure may not reflect the real coupled effects under multiple loads and environmental actions. Other common questions are that the accelerated durability test results may not reflect the real effects of a structure exposure to real harsh environment, and the test results of the small scale model may be different from those of the full-scale test due to scale effects.



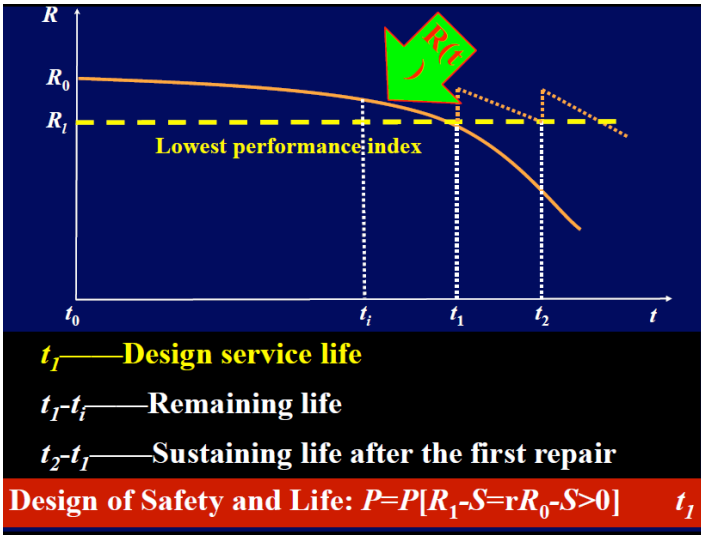
How will we know the life-cycle performance —Ideal testing method for investigating change in life-cycle performance caused by environmental actions



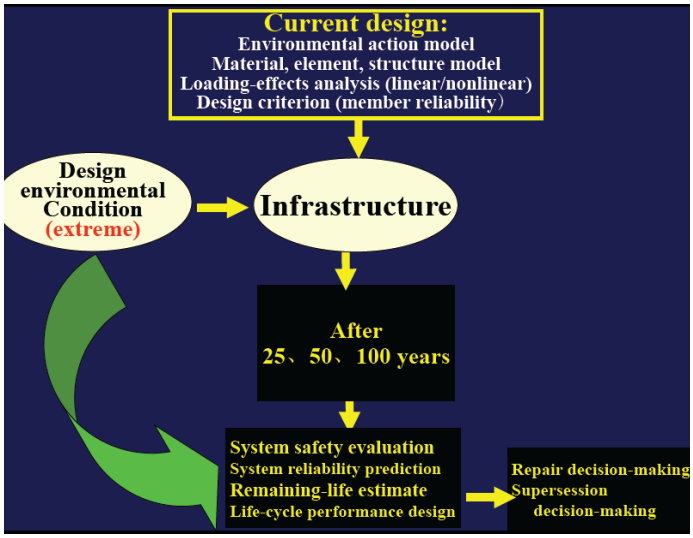
How will we know the life-cycle performance—Ideal testing method for obtaining resistance deterioration caused by fatigue damage

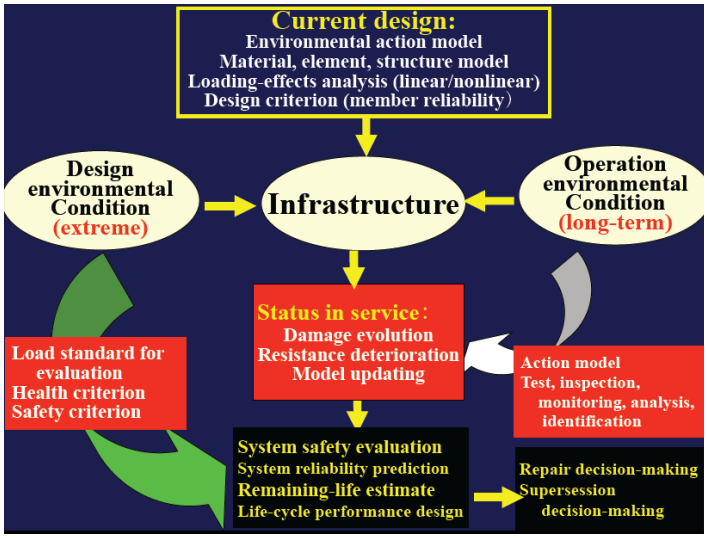


Multiple-factors and their coupled effects for life-cycle performance evaluation



Life-cycle design with accounting deterioration of life-cycle performance

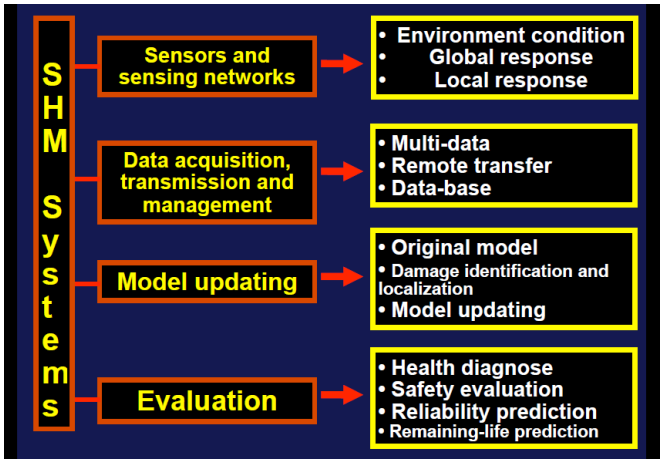




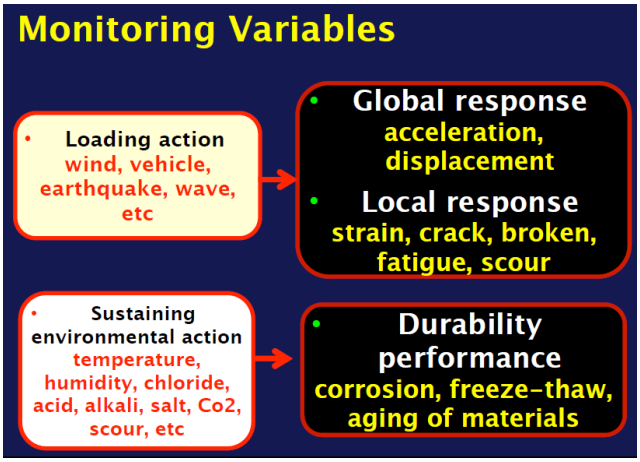
Frame-work from current design methodology stepping to life-cycle design methodology

Structural health monitoring system SHM provides a powerful tool to investigate the real behavior and life-cycle performance of a structure under known and unknown multiple loads and environmental actions together. A SHM system on a full-scale structure plays a role of an *in-situ* test system. Exact load and environmental action models and their parameters can be obtained through SHM, and the load in remain service period can then be predicted; the finite element model or simplified model (e.g. response surface method) can be updated through SHM data, and the deterioration in resistance can be obtained by using the updated model. In this way, the time-variant reliability can be predicted based on SHM. Once the reliability of the structure decrease to a certain threshold, a decision on the maintenance action (e.g. repair or rehabilitation) can then be made to increase structural safety to an expected level. It should be noted that the failure modes may be easily found because the load patterns and deterioration in resistance of elements may be exactly obtained through SHM data.

The first question is "What is the health of infrastructure?" It would include all factor changes resulting in the deterioration of the performance such as safety, serviceability, durability, sustainability of infrastructures. SHM plays more and more important role in the life-cycle performance evaluation and design of infrastructure. A SHM system should at least include, but not limited four sub-systems, i.e. sensors and sensing networks, data acquisition, transmission and management, model updating and evaluation. The second issue is what variables should be measured. The variables can be categorized into loads and their responses (such as earthquake ground motion, wind load, vehicle, wave, global response including acceleration, displacement, inclination, etc., and local response including strain, fatigue, crack, tension in cable, breakage, etc.), and environmental actions and their-induced durability performance of the structure (such as temperature, humidity, chloride, alkali, acid, flood, carbon dioxide, corrosion, freeze-thaw cycle, scour, ageing of materials, etc.).



Sub-systems and their functions of a SHM system



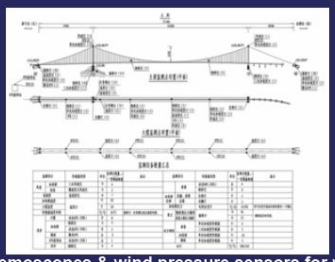
Variables should be measured by SHM system

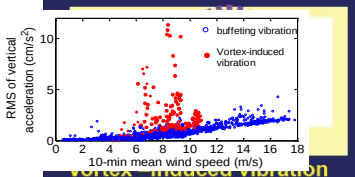
A lot of advanced sensors have been developed for monitoring long-term loads, actions, responses and performance for recent two decades, such as optical fiber sensing technology, piezoelectric ceramic array sensors, corrosion sensors, cement-based sensors, and some NDT techniques (ultrasonic sensors, acoustic emission sensors, microwave technique, etc.). The wireless sensor networks and distributed sensing networks will be potential tools to solve the challenge issues in SHM. Nanomaterial-based sensing technology and bio-inspired sensing technology are emerging now. Although the sensor technology has been well developed, there still are some challenge issues to be solved in the future, such as the quality of data, reliability and stability of sensors for long-term service, and monitoring for durability (chemical variables) and stress distributed at the interface.

As Prof. Ansari's previous notes, a number of sophisticated SHM systems have been implemented into many structures in China, such as long-span bridges, buildings, offshore platforms, etc. (here show several examples). It can be seen that the sensor are not only installed on upper-structure, also pile foundations and piers for monitoring of corrosion and scour. The sensors (wind anemoscope, wind pressure sensors, temperature sensors, humidity sensors, weigh-in-motion, rainfall, accelerometers, displacement transducers, GPS, tilt meters, sensors for cable tension, strain gauge, ultrasonic sensors, radar, corrosion sensors, etc., are included in the SHM systems. Besides sensors, the software for data acquisition, transmission, and management has been developed, and the SHM systems can be automatically operated and managed through internet. SHM technique has been into industry commercial area five years ago.

Xihoumen Bridge

------Longest span suspension bridge (CCCC, HIT)





Vortex-induced vibration has occurred at 5-10m/s, warning for traffic

- 9 Anemoscopes & wind pressure sensors for wind
- Accelerometers for vibration & earthquake ground motion
- Weigh-in-motion
- GPS for vibration of main cables
- Inclinometer for tower deformation and suspenders
- Temperature & humidity sensors
- Strain gauge
- Sensors for cable force

Jiading-Chaoxing Bridge

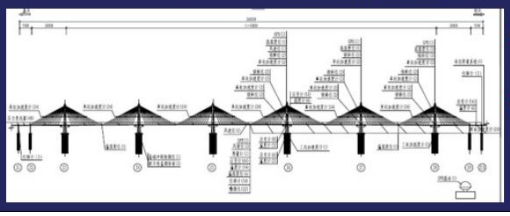
------6-tower cable-stayed bridge (CCCC)

- Anemoscopes
- Accelerometers
- Weigh-in-motion
- GPS
- Inclinometer
- Temperature & humidity sensors
- Strain gauge
- Transducers

Upper structure

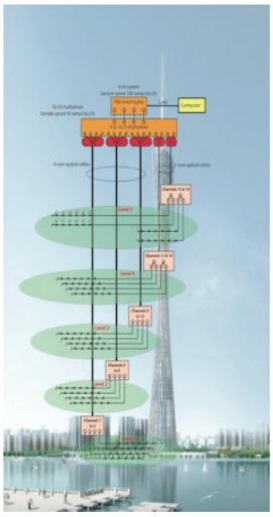
- Rainfall
- Radar, ultrasonic sensors for scour
- Corrosion sensors

Lower structure

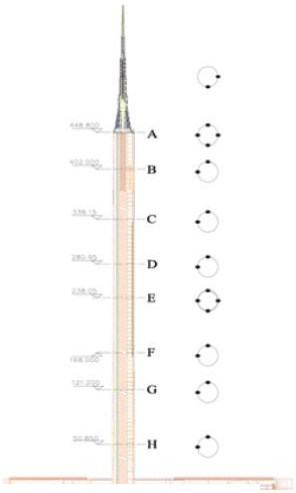


- Very complicated hinge support at mid-span
- A number of strain gauge , transducers & video are installed

Deployment of FBG sensors



Deployment of accelerometers

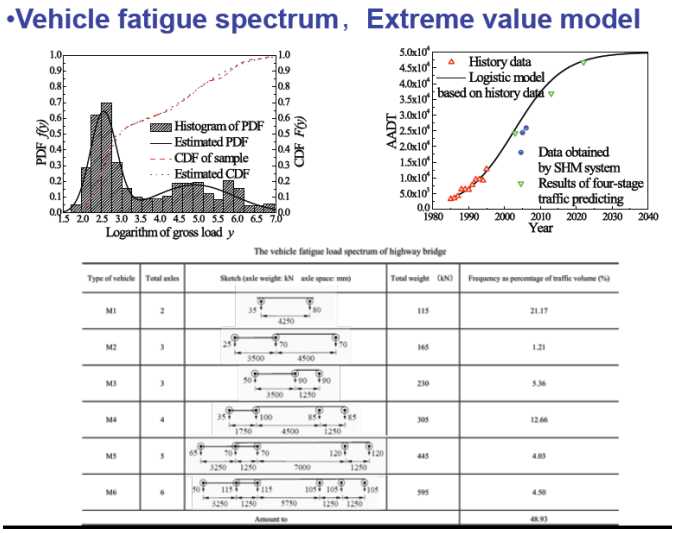


Guangzhou New TV tower

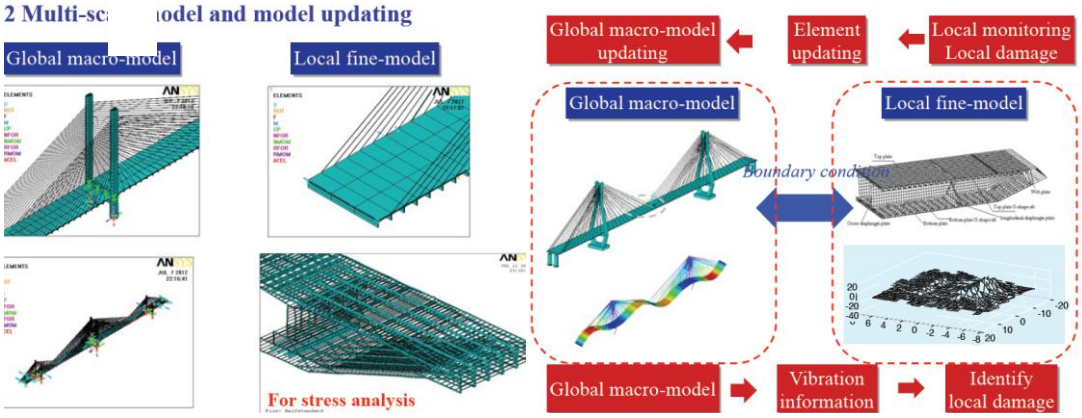
Applications of SHM systems in various infrastructures

Data process, data analysis, data mining, data modeling, performance evaluation and condition assessment based on SHM are other challenge but most concerned issue by infrastructure managers, engineers and experts. In China, data has been obtained from the operating SHM systems. The measured data may be incorrect or contaminated by strong noise, e.g. data packet loss has been observed in wireless sensors network, and the monitored wind speed may be impacted by rainfall during hurricane events. Some data process approaches have been proposed to improve data quality and will be reported in *Monitor* by my group at HIT. Based on monitored data, the models of loads and environmental actions, such as extreme value model and fatigue model of vehicles, wind and wave, the models of

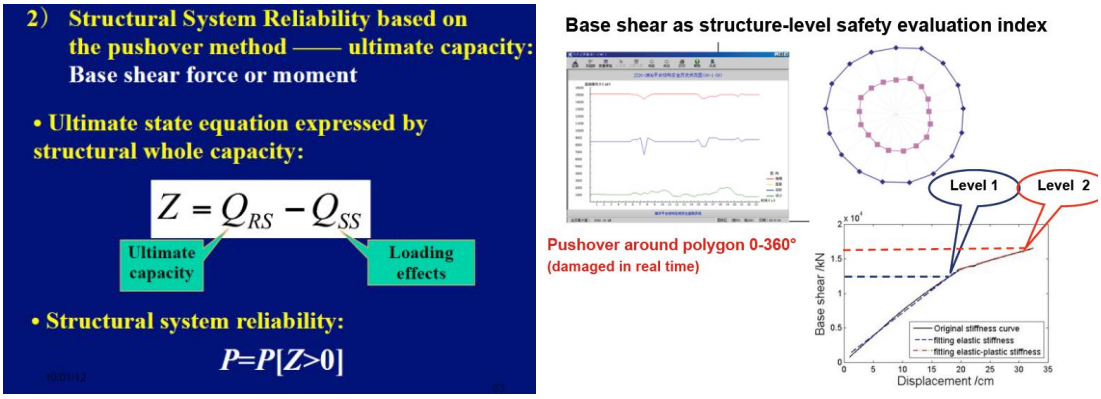
temperature, acid, alkali, chloride actions etc., can be statistically established; the extreme value model of response and fatigue accumulated damage model of the structures, and the corrosion extent of the rebar and steel elements can also be obtained based on monitored data. The multi-scale model of a structure can be updated to obtain more exact structural analysis model (for critical structural member or substructure, solid finite element model is needed; while for other structural members and substructures, beam finite element model is enough). Model updating approaches for obtaining more exact multiple-scale model have been proposed by Chinese experts. The response at the locations without sensors can be calculated by using the updated model (for stochastic disturbance, Kalman filer may be employed to estimate the response at the locations without sensors) and the deterioration in resistance can be obtained by using the updated multiple-scale model. Finally, the life-cycle performance and safety level of the civil infrastructure can be evaluated and predicted based on load and environmental action models, response models and updated structural model, which provides a basis for the life-cycle performance design of civil infrastructures.



Models of vehicles based on monitored data

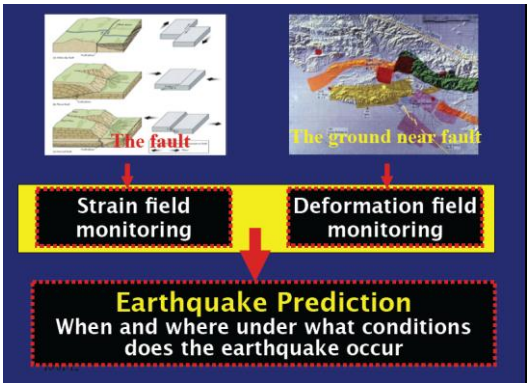


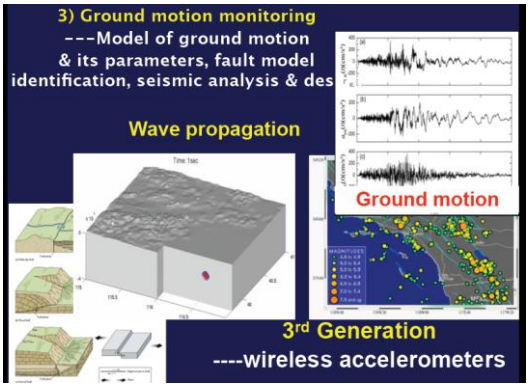
Multiple scale model and model updating

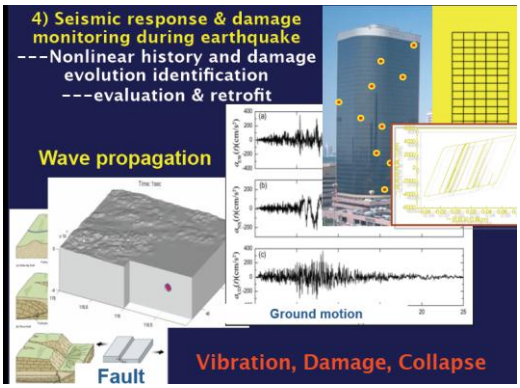


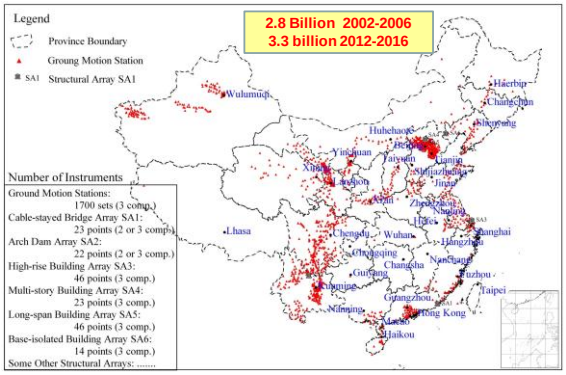
Safety evaluation of whole offshore platform structure based on SHM

Infrastructure may be subjected to earthquake attacks. Therefore, the ground motion and earthquake-induced vibration of structures should be included in the SHM system. In fact, monitoring for ground motion started much earlier than the birth of SHM concept. In 1931, accelerometers for strong ground motion monitoring was invented and were implemented along Long Bench at Los Angles, and first record of strong ground motion was obtained in next year (1932). In addition, if we can install the sensors on fault and monitoring occurrence of earthquake event, it will aid us to understand the mechanism of earthquake form and occurring. Based on the monitored ground motion, we also can identify the model and parameters of earthquake fault. The early warning of an earthquake event based on monitored P-wave and S-wave has been proposed by researchers. Based on the monitored ground motion and the corresponding structural vibration, we can understand the real behavior of a structure subjected to earthquake ground motion; we can validate the structural analysis and design methods of earthquake engineering, detect damage and assess the residual seismic capability of a structure. Chinese government has invested 6.1 billion RMB to set up the seismic ground motion observatory around the whole country (including the earthquake response of structure), which will cover all strong earthquake zones in China. A China-US collaborative project supported by NSFC (China) and NSF (the US) has been granted (Chinese PI: Hui Li at HIT, the US PI: Billie F Spencer at UIUC). Shaking table test of a 16-story steel moment resistant frame with Imote-2 wireless sensors (Billie F Spencer developed) has been performed at HIT through collaboration of HIT, DUT and UIUC, and a data-driven approach for localizing damage has been proposed and it is validated through the shaking table test.






4) Seismic response & damage monitoring during earthquake
---Nonlinear history and damage evolution identification
---evaluation & retrofit
Wave propagation
Ground motion
Fault
Vibration, Damage, Collapse


Legend
Province Boundary
Groung Motion Station
SA1 Structural Array SA1
2.8 Billion 2002-2006
3.3 billion 2012-2016
Number of Instruments
Ground Motion Stations:
1700 sets (3 comp.)
Cable-stayed Bridge Array SA1:
23 points (2 or 3 comp.)
Arch Dam Array SA2:
22 points (2 or 3 comp.)
High-rise Building Array SA3:
46 points (3 comp.)
Multi-story Building Array SA4:
23 points (3 comp.)
Long-span Building Array SA5:
46 points (3 comp.)
Base-isolated Building Array SA6:
14 points (3 comp.)
Some Other Structural Arrays: .....
Wulumuqi
Lhasa
Haerbin
Changchun
Huhehaote
Yinchuan
Taiyuan
Xining
Lanzhou
Shijiazhuang
Jinan
Zhengzhou
Nanjing
Hefei
Shanghai
Chengdu
Wuhan
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Macao
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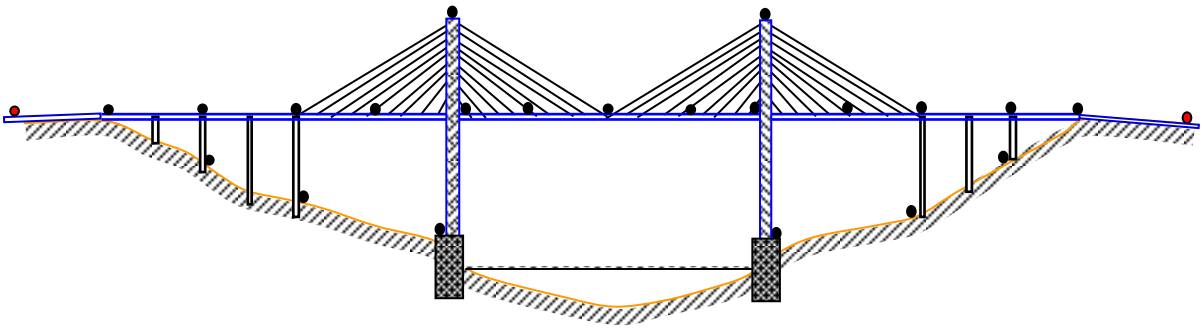

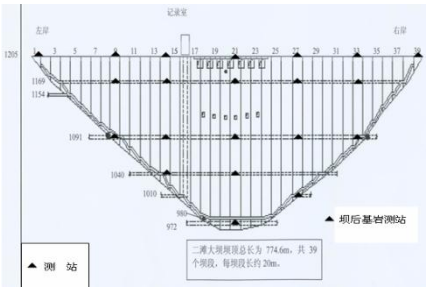
记录室
左岸
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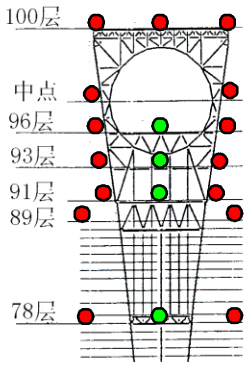
坝后基岩测站
测 站
二滩大坝坝现总长为 774.6m，共 39 个坝段，每坝段长约 20m。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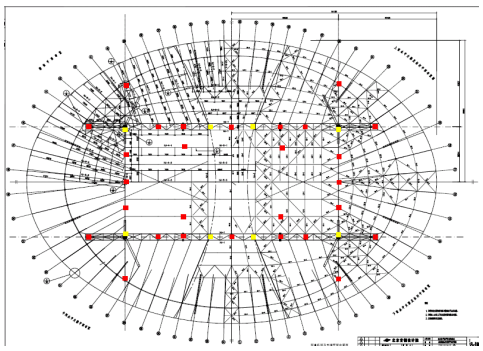
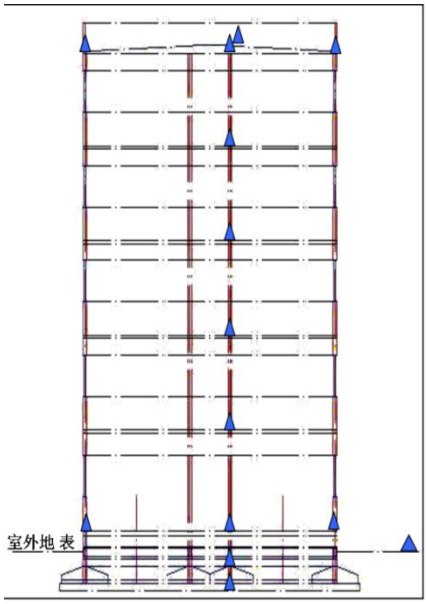
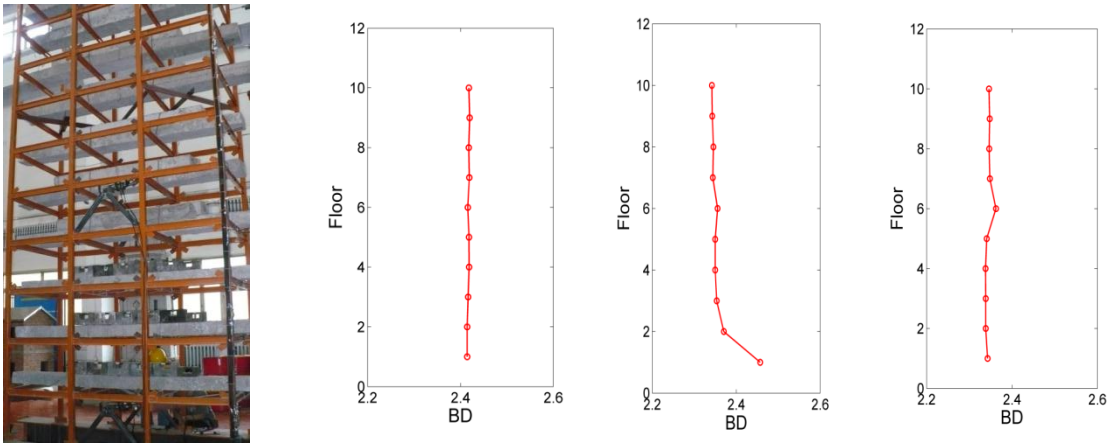
78层



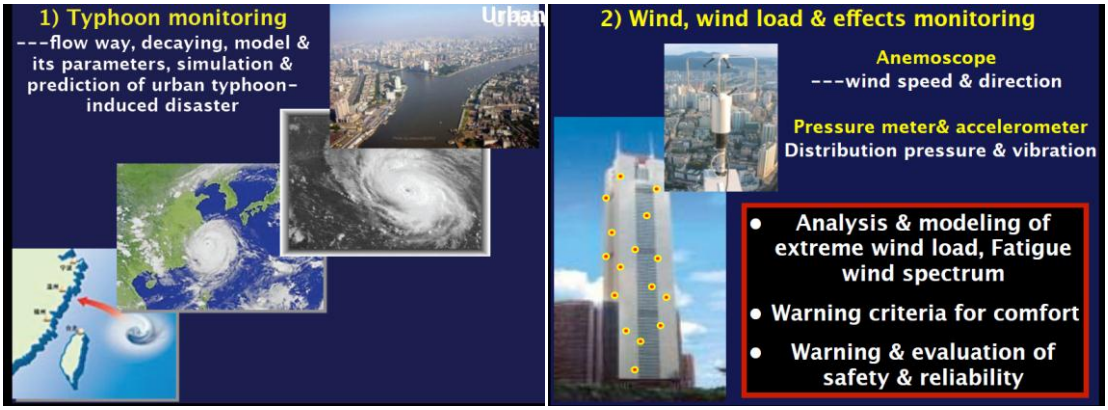


Seismic ground motion observatory



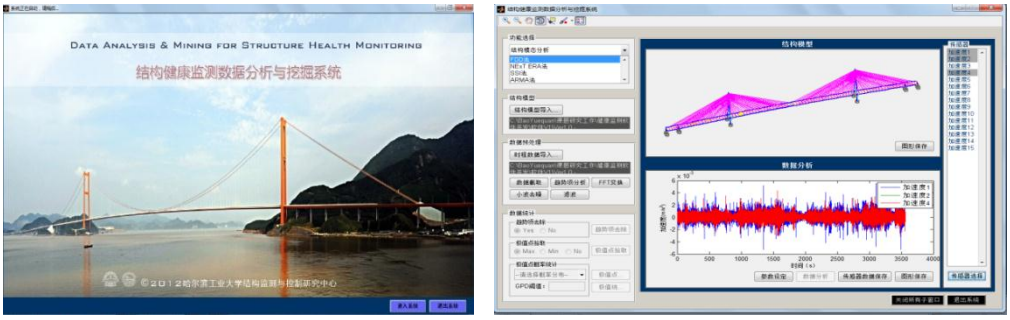
Seismic damage monitoring of a 16-story structure by using Imote-2 wireless sensors network

Wind and wind effect should be included SHM systems for the flexible structures located in strong wind areas. In some area, wind is very strong and it will induce large deformation and dramatic vibration for long-span bridges, tall buildings, offshore platform, wind energy turbine systems and electric power plant systems. The wind and wind effect on structures should also be included in SHM systems. The SHM system can monitor hurricane over a region or a city, which will be useful to investigate behavior of hurricane on land. In addition, wind speed, wind load and wind effects on a structure are also monitored to investigate the real behavior of a structure under wind. The monitored data can be used to validate exiting theories and methods in wind engineering, to develop new structural analysis approaches for wind engineering, and to research some critical problems in wind engineering (e.g. Reynolds number effects, spatial correlations, etc.). NSFC (China) has supported several key projects relevant with field monitoring of wind and wind effects on tall buildings, long-span bridges and flexible spatial structures.



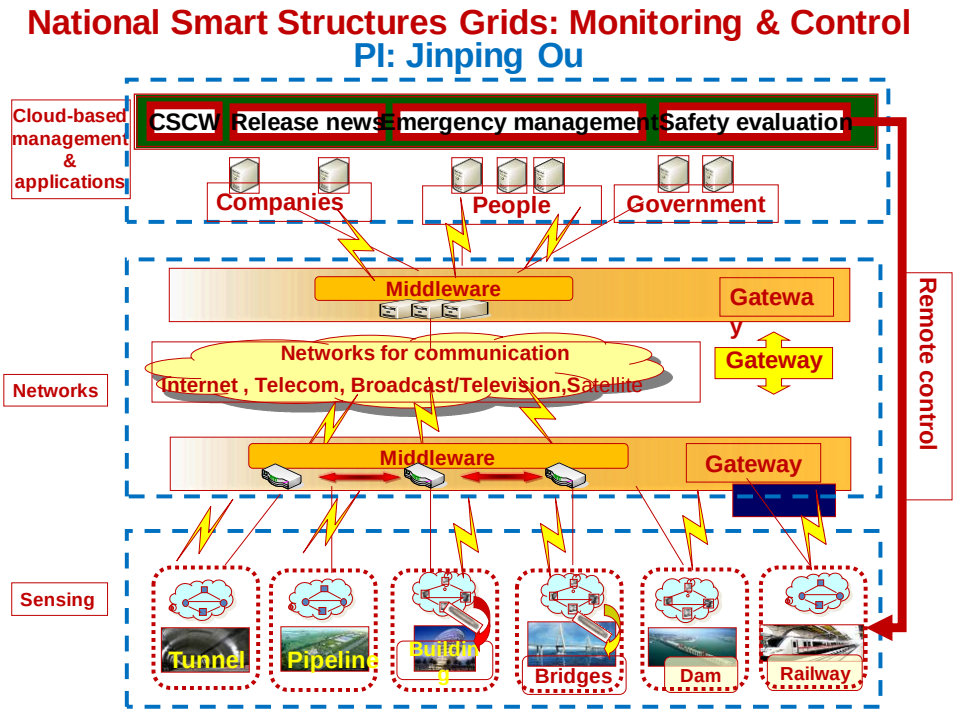
Monitoring for wind, wind load and wind effects over a regional area and structures

Based on the research and practice on SHM, my group at HIT has completed the software for data processing, data analysis, data mining, data model and safety evaluation, including long-term performance, seismic damage detection and wind effects analysis.



Software for data processing, data analysis, data mining, data modeling and safety evaluation based on SHM

National Smart Structures Grids: Monitoring and Control. Recent years, Chinese government supports an R & D program on National Smart Structures Grids, which integrates monitoring, data transmission, decision-making and control together for all critical infrastructures across the whole country.



National Smart Structures Grids: Monitoring and Control (China)

Education in SHM. Finally, I would like to talk about education of SHM in China. From 2005, we have set courses on SHM, including advanced sensing technology, modal analysis, and vibration-based damage detection for undergraduate students and graduate students at HIT (two years ago, we added contents of data analysis, mining, modeling and safety evaluation). Besides HIT, DUT, Tongji University, Southeastern University, Xiamen University, etc., also have SHM courses for graduate students. Additionally, several other associations have summer schools for educating SHM. ISHMII may set up a course of SHM for educating and training students and engineers, what I will talk in the future.

With Best Regards,

Jinping Ou

Vice President, Member Education

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