WESTERN SYDNEY UNIVERSITY

Research

Structural Health Monitoring based on Vehicle-Bridge Interaction

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Outline

- Background
- Bridge Condition Assessment based Damage Indicators
- Bridge Monitoring based on Advanced Signal Processing
- Bridge Health Monitoring
  - Using the instrumented bridge
  - Using the instrumented vehicle
- Conclusions and Recommendations
- Sensor Technology Development

BACKGROUND

Structural Health Monitoring (SHM)

- Ageing Infrastructure
- Growing population accelerates ageing and deterioration
- Earlier deterioration due to poor construction quality and heavy usage by overloaded vehicles

Partial Solution

- More cost-effective management of ageing infrastructure
- Condition-based maintenance and longer-service lives

Sydney Harbour Bridge – Rail/Highway, 19 March 1932

Length-1149m, arch span--503m, height-134m.

159,597 vehicles per day in 2001.

BACKGROUND

Monitoring Requirements of medium-span Bridges

- Large stock of bridge structures—the monitoring should be a technically simple process
- Cost of implementation—should not be a labour intensive process
- Minimum disturbance to traffic—rapid measurement process
- Short-term monitoring—no permanent installed sensors
- To have a sufficient description on the damage for Engineers to make the decision—the type of the damage, residue of the prestress etc.

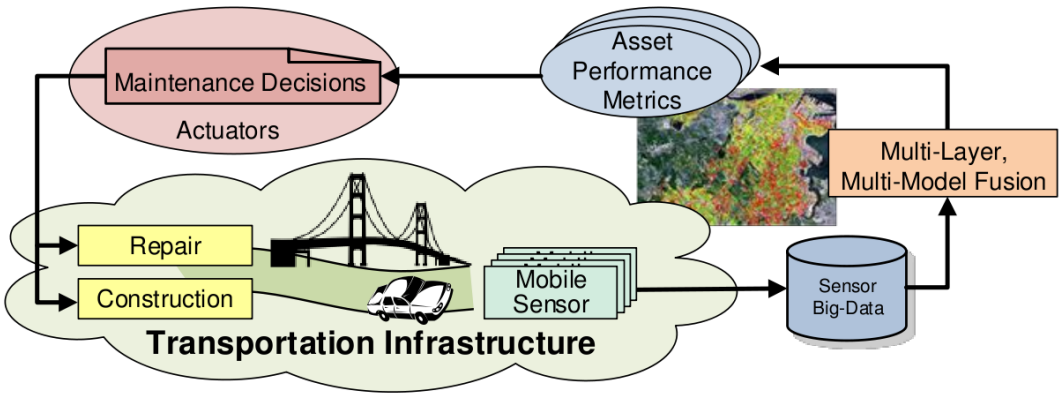
To address the bridge safety problem:

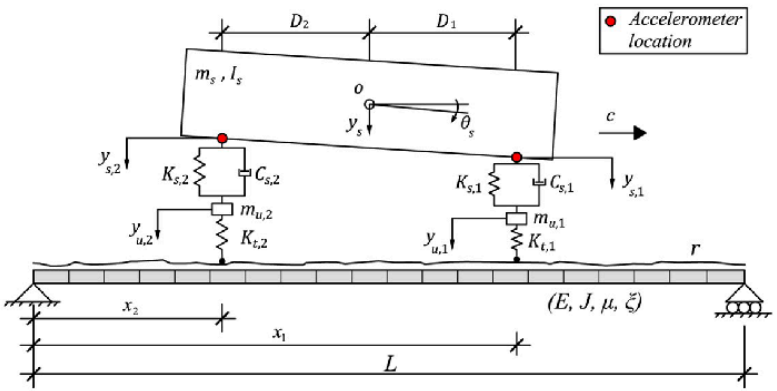
- the control of overloaded trucks
- the safety assessment/monitoring of bridges

Medium-span bridge structures

Instrumented vehicle (radar)

BACKGROUND



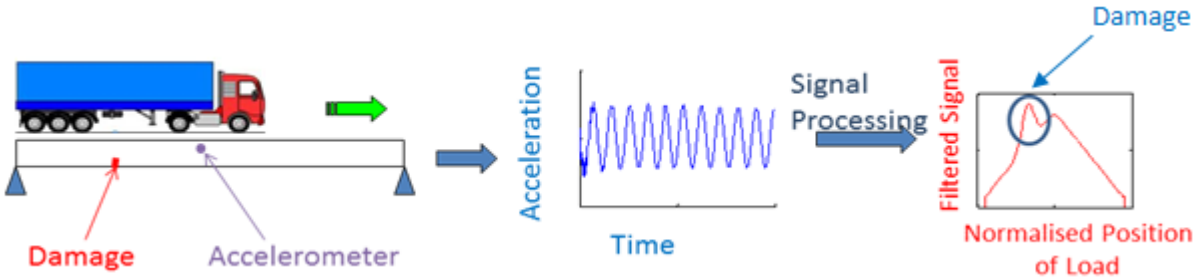


- Vehicle-bridge interaction refers the dynamic coupling forces between vehicles and a bridge when vehicles cross the bridge.
- A complete understanding of this complex coupling is critical for bridge design, bridge condition assessment, overweight vehicle control, etc.
- This presents a review of the past and recent developments in bridge health monitoring based on vehicle-bridge interaction dynamics.

BACKGROUND

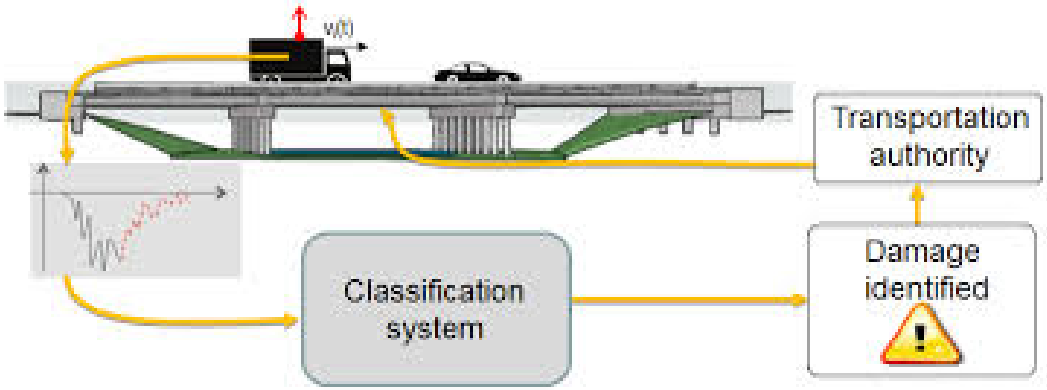
Instrumented bridge:

- The moving vehicle is an moving excitation.
- Bridge responses are monitored.
- Bridge condition assessment is based on bridge responses.
- A video-assisted approach could provides the traffic information.

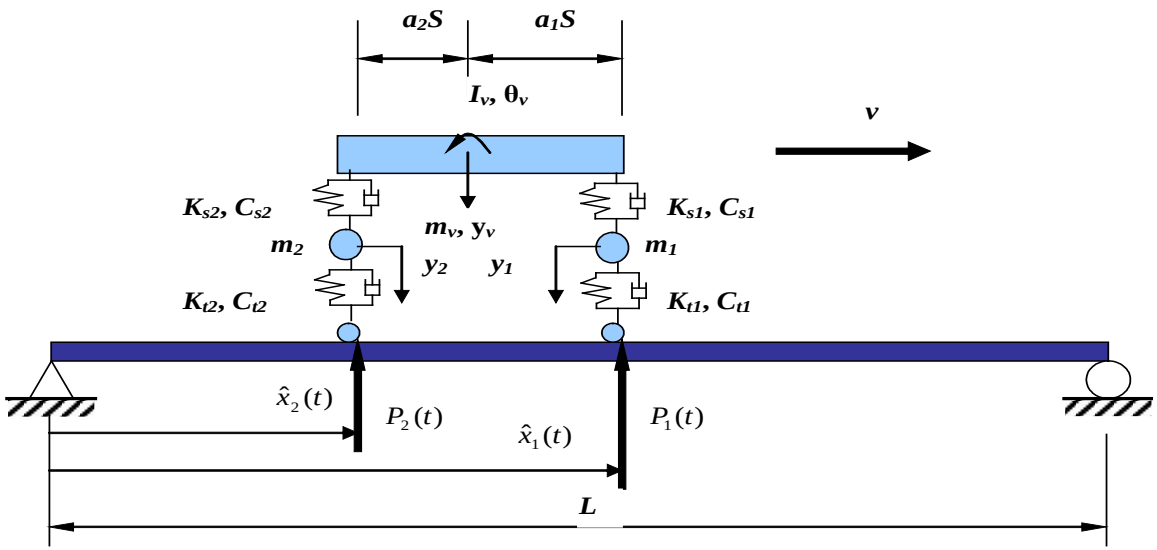


Instrumented vehicle:

- The moving vehicle is a moving sensor to capture the bridge information.
- A passing vehicle to scan the bridge.
- A moving vehicle to catch the bridge response information.



Vehicle-Bridge Interaction System



Vehicle Model

$$\boldsymbol{M}_v\ddot{\boldsymbol{Z}} + \boldsymbol{C}_v\dot{\boldsymbol{Z}} + \boldsymbol{K}_v\boldsymbol{Z} = \boldsymbol{F}_v^{\text{int}}$$

Bridge Model

$$\mathbf{M}_b\ddot{\mathbf{Q}} + \mathbf{C}_b\dot{\mathbf{Q}} + \mathbf{K}_b\mathbf{Q} = H_b\mathbf{F}_b^{\text{int}}$$

Vehicle-Bridge System Model

$$\mathbf{M}(t)\ddot{\mathbf{D}} + \mathbf{C}(t)\dot{\mathbf{D}} + \mathbf{K}(t)\mathbf{D} = \mathbf{F}(t)$$

Road surface Roughness

$$r(x) = \sum_{i=1}^{N}\sqrt{4S(f_i)\Delta f}\,\cos(2\pi f_i x + \theta_i)$$

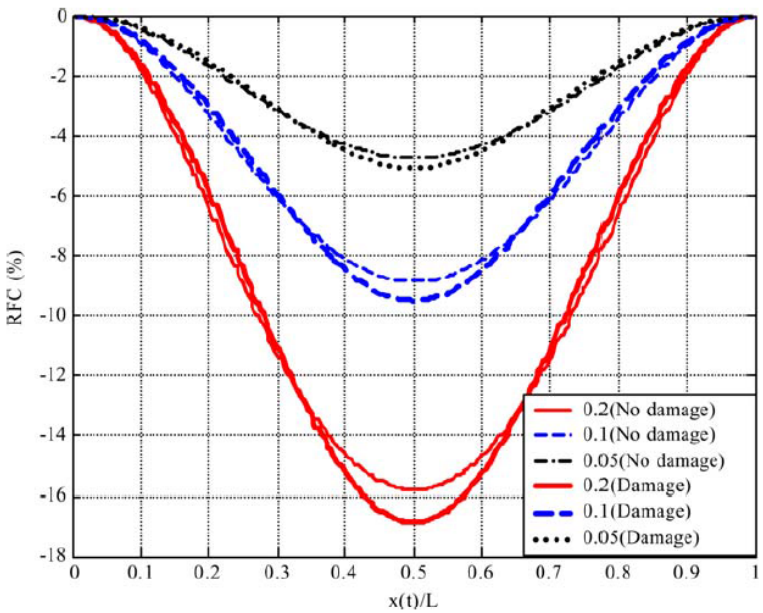
Nonlinear Characteristics of damaged Bridges subjected to Moving Vehicles

- Nonlinear characteristics
  - Relative frequency change
  - Normalized deflection
  - Phase plane plot
- These dynamic features could be potential damage indicators.

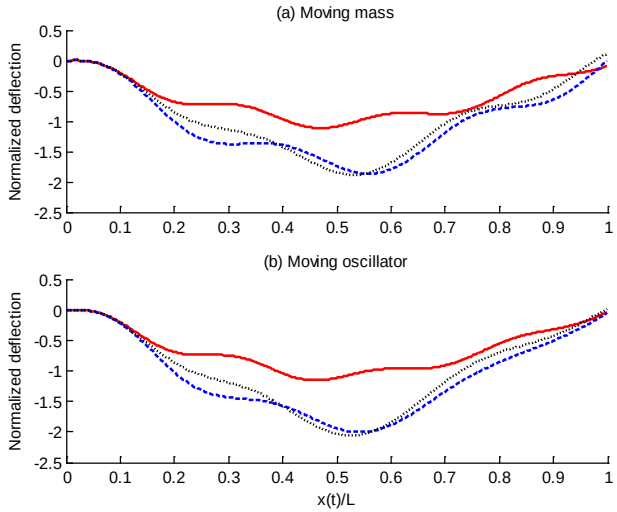
Relative frequency change:

- It is defined as the percentage change between the frequency of the bridge subjected to a passing vehicle to the first natural frequency of the bridge.

$$\begin{cases} AFC = \dfrac{\omega - \omega_n}{\omega_n} \times 100\% \\ RFC = \dfrac{\omega - \omega_0}{\omega_0} \times 100\% \end{cases}$$



Nonlinear Characteristics of Bridge under Moving vehicular Loads

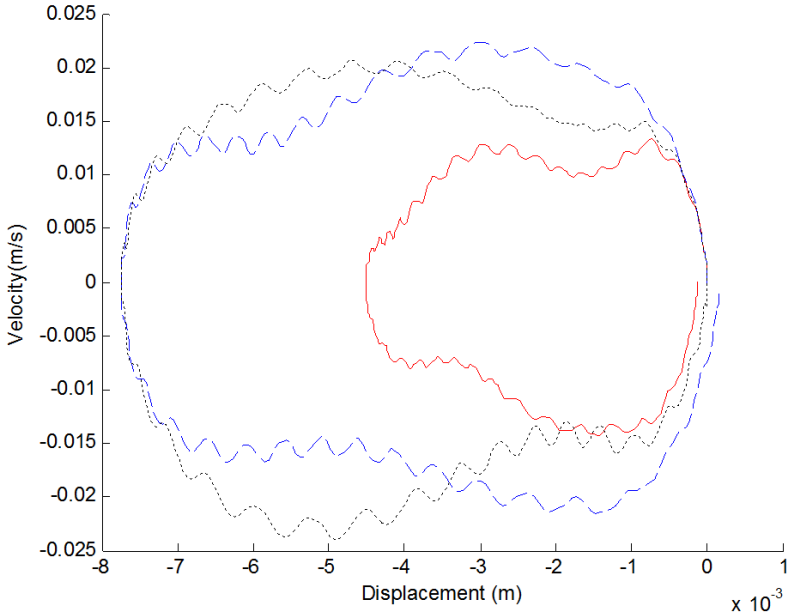


Normalized deflection:

- The damage in the bridge structure subjected to vehicular loads leads to a deflection change.
- It is difficult to measure in practice.

Phase Plane Plot:

- The damage causes a change in the phase space topology of the response.
- The change in the phase space geometry could be a damage indicator of damage in the bridge structure.



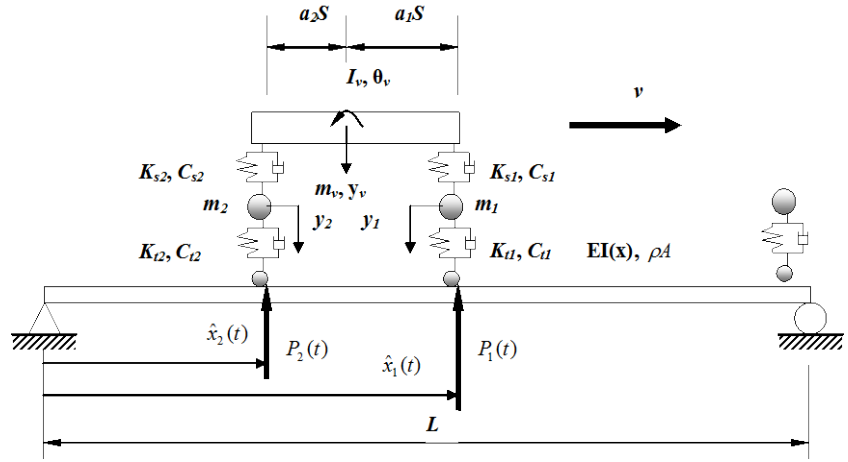
Bridge Damage Detection using Advanced Signal Processing

Advanced signal processing:

- **Wavelet transform**—extract the discontinuity of the structural response due to the local damage.
- **Hilbert-Huang transform**—for nonlinear and non-stationary signal processing, the signal is decomposed into intrinsic mode functions and the discontinuity could be inspected using the first instantaneous frequency.

Bridge Damage Detection using Advanced Signal Processing

Bridge response at a single point:



$$y(x_m,t)=\sum_{k=1}^{\infty}\left\{\frac{\phi_k(x_m)}{M_k}\left[h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\phi_k(x_i(t))\right)\right]\right\}$$

$$\frac{\partial^2 y(x_m,t)}{\partial x_j(t)^2}=\sum_{k=1}^{\infty}\left\{\frac{\phi_k(x_m)}{M_k}\left[h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\frac{\partial^2\phi_k(x_i(t))}{\partial x_j(t)^2}\right)\right]\right\}$$

mode shape curvature

Wavelet Transform:

$$Wy(x_m,s)=y(x_m,t)\otimes\frac{\partial^2\theta_s(x_j(t))}{\partial x_j(t)^2}$$

$$=\sum_{k=1}^{\infty}\left\{\frac{\phi_k(x_m)}{M_k}\left[h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\phi_k(x_i(t))\right)\otimes\frac{\partial^2\theta_s(x_j(t))}{\partial x_j(t)^2}\right]\right\}$$

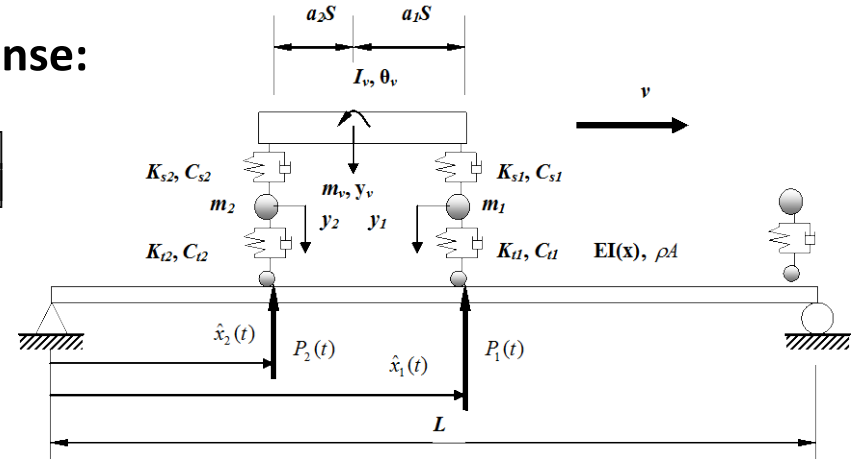
$$=\sum_{k=1}^{\infty}\left\{\frac{\phi_k(x_m)}{M_k}\left[h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\frac{\partial^2\phi_k(x_i(t))}{\partial x_j(t)^2}\right)\otimes\theta_s(x_j(t))\right]\right\}$$

$$=\frac{\partial^2 y(x_m,t)}{\partial x_j(t)^2}\otimes\theta_s(x_j(t))$$

Bridge Damage Detection using Advanced Signal Processing

Wavelet Transform from the acceleration response:

$$W\ddot{y}(x_m,s)=\frac{\partial^2\ddot{y}(x_m,t)}{\partial x_j(t)^2}\otimes\frac{d^2\theta_s(x_j(t))}{dt^2}=\frac{\partial^2 y(x_m,t)}{\partial x_j(t)^2}\otimes\left[v_j^2\theta_s''(x_j(t))\right]$$



Using the vehicle response:

$$Z_i(t)=h_{vi}(t)\otimes u(x_i(t))$$
$$=h_{vi}(t)\otimes\left[y(x_i(t),t)+r(x_i(t)\right]$$

$$u(x_i(t),t)=y(x_i(t),t)+r(x_i(t))$$

$$W\ddot{Z}_j(t)=\ddot{Z}_j(t)\otimes\frac{\partial^2\theta_s(x_j(t))}{\partial x_j(t)^2}$$

$$=\ddot{h}_{vj}(t)\otimes(y(x_i(t),t)+r(x_i(t))\otimes\frac{\partial^2\theta_s(x_j(t))}{\partial x_j(t)^2}$$

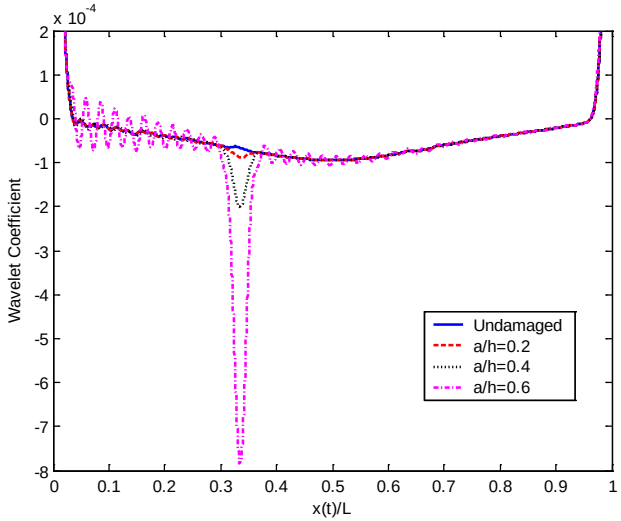
$$=\ddot{h}_{vj}(t)\otimes\left\{\sum_{k=1}^{\infty}\left[\frac{\phi_k(x_j(t))}{M_k}\right]\left[h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\frac{\partial^2\phi_k(x_i(t))}{\partial x_j(t)^2}\right)\otimes\theta_s(x_j(t))\right]\right\}$$

$$+\ddot{h}_{vj}(t)\otimes\left(\sum_{k=1}^{\infty}\left[\frac{1}{M_k}\frac{\partial^2\phi_k(x_j(t))}{\partial x_j(t)^2}\right]\left\{h_k(t)\otimes\left(\sum_{i=1}^{n}P_i(t)\phi_k(x_i(t))\right)\otimes\theta_s(x_j(t))\right\}\right)$$

$$+\ddot{h}_{vj}(t)\otimes r(x_i(t))\otimes\frac{\partial^2\theta_s(x_j(t))}{\partial x_j(t)^2}$$

mode shape curvature

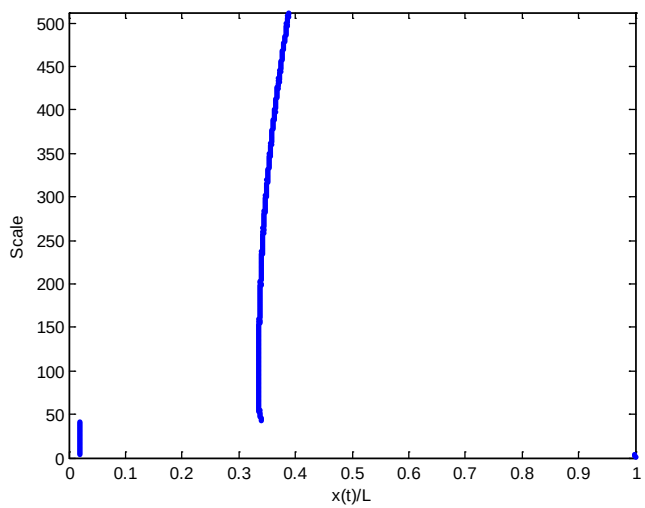
Bridge Damage Detection using Advanced Signal Processing

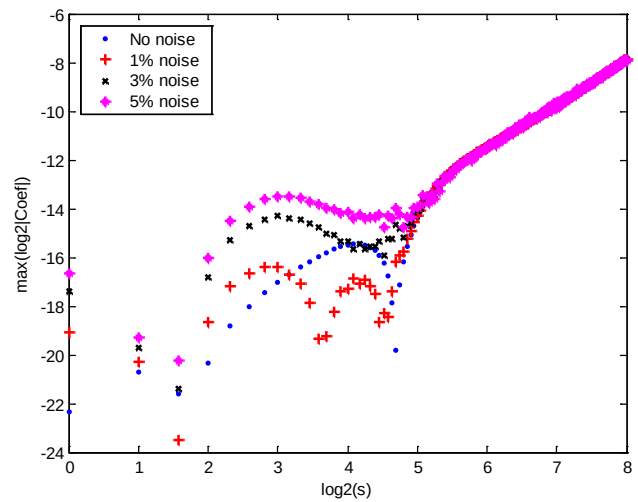


Wavelet coefficients with various crack depth and 3% noise in the response

Wavelet Transform:

- The mode shape of a structure with a local damage will contain a discontinuity at the damage point.
- The wavelet transform can be used to replace the direct differentiation of the displacement to get the curvature properties.
- The damage can then be located using the wavelet transform of the response time history at one point when the beam structure is subject to the action of the moving load.

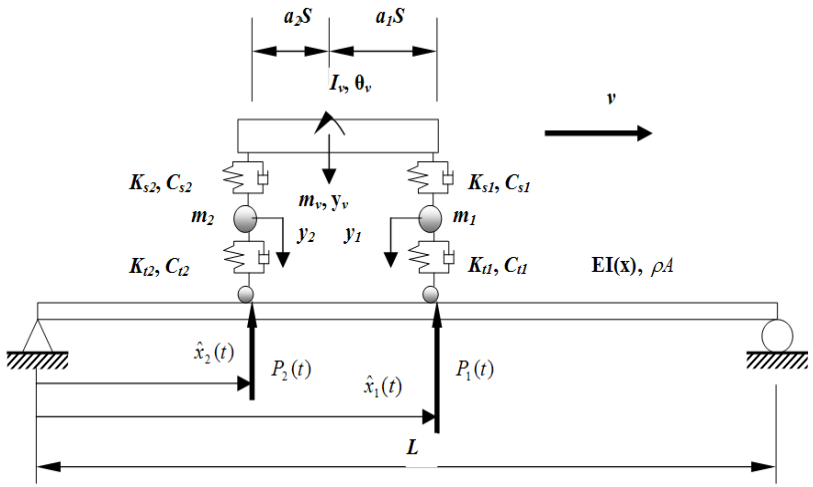


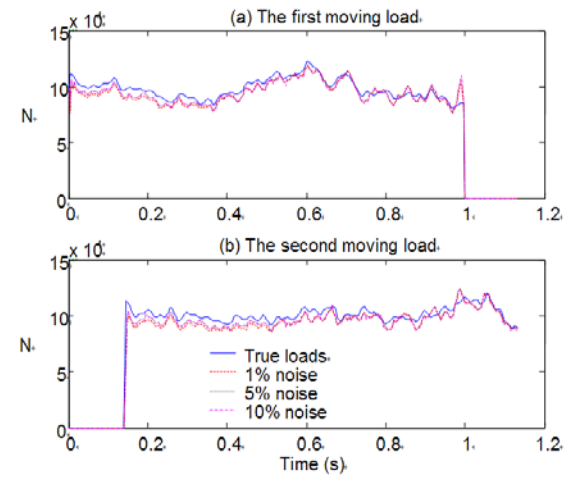


Structural Identification using an Instrumented Bridge

- **Bride parameter identification based on unknown traffic excitations:** a common assumption in the output-only identification is the white noise input, such as the natural excitation technique, the frequency domain decomposition, stochastic subspace identification and autoregressive-moving-average model techniques.
- **Bridge condition assessment based on traffic monitoring:** a video-assisted approach for structural health monitoring of highway bridges. Videos of passing vehicles are captured and synchronized with data recording from the instrumented bridge.
- **Iterative procedure for vehicle-bridge system identification**: a method for simultaneous identification of the interaction force time histories and structural parameters iteratively using a two step identification procedure with responses of the bridge subjected to moving vehicular loads that serve as input.

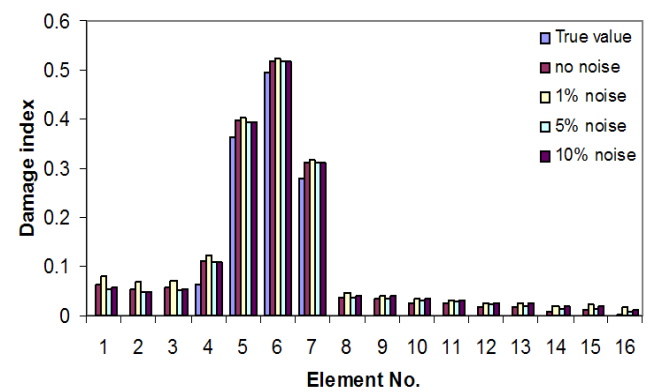
Iterative procedure for vehicle-bridge system identification





Moving load identification

- The 30m long bridge is divided into 16 beam elements with 15 strain measurements.
- The first six natural frequencies are 3.90, 15.61, 35.13, 62.45, 97.58 and 140.51Hz.
- There are 4 DOFs in the vehicle with the natural frequencies of 1.63, 2.30, 10.35 and 15.10 Hz.
- Axle spacing is 4.27m. The vehicle-bridge weight ratio is 0.135. Travel speed of vehicle is 30m/s.
- Sampling rate is 250 Hz.
- Class B road surface roughness is used.

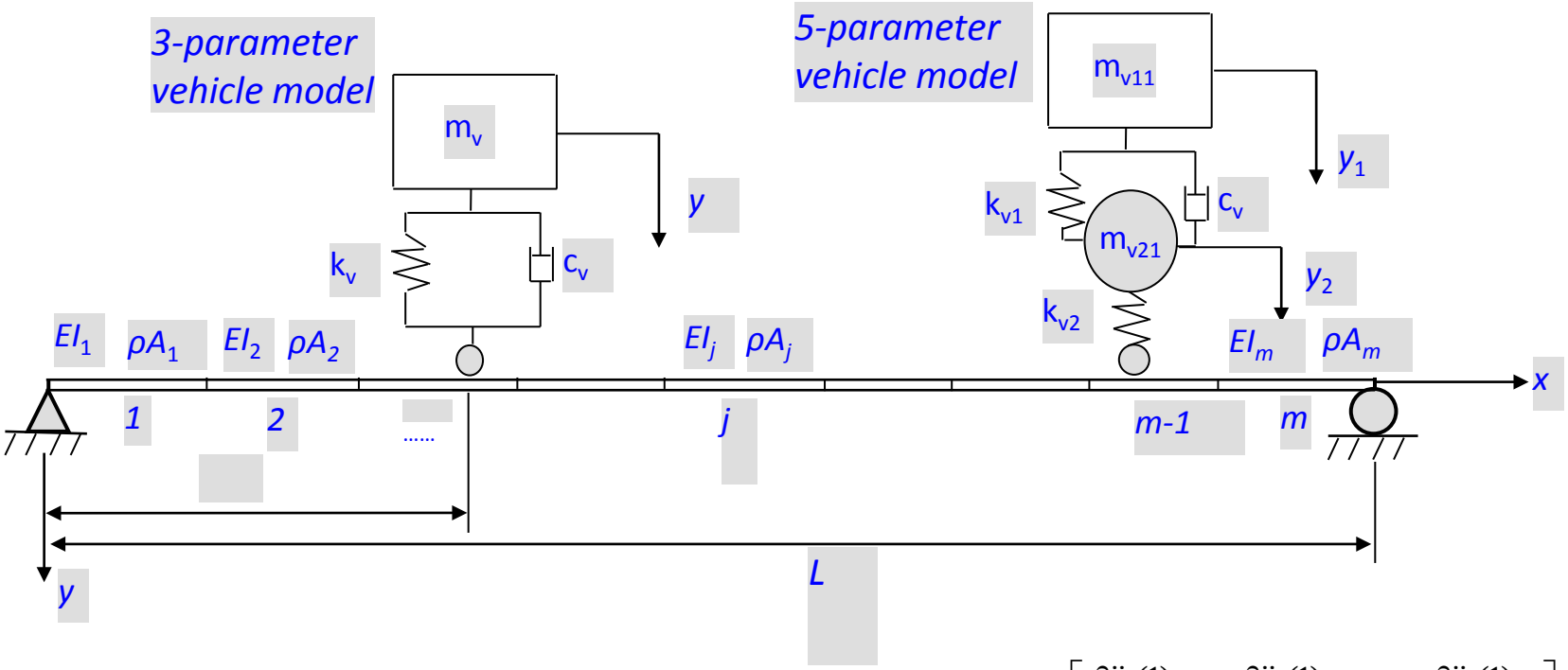


Damage detection using multiple sensors

Indirect Bridge Structural Health Monitoring

- **Extracting the bridge dynamic properties from vehicle responses:** 1) the vehicle can serve as both a moving exciter and a sensory system to capture the vehicle-bridge interaction information; 2) the vehicle serve as a sensory system only to capture the bridge response information.
- **Bridge condition assessment from vehicle responses:** Sensors are installed only on the vehicle as moving sensors collecting data at different locations of the structure which is equivalent to a dense array of sensors. Local damage in a region trepassed by the vehicle can be more readily and accurately identified by the local responses collected due to the higher sensitivity.
- **Wireless sensor networks for vehicle-bridge system identification**: With the development of the wireless sensory system, the truck-based mobile wireless sensor network is one of the more cost effective approaches to capture the dynamic interaction between the vehicles and the bridge.

Indirect Bridge Structural Health Monitoring



Equation of motion:

$$M\ddot{S} + C\dot{S} + KS = P$$

Bridge parameter identification using regularization techniques:

$$J(\Delta p_r, \lambda) = \left\| \bar{S}_r \Delta p_r - \Delta \ddot{v}_r \right\|^2 + \lambda \left\| \Delta p_r \right\|^2$$

$$\bar{S}_r = \begin{bmatrix} \frac{\partial \ddot{v}_r(1)}{\partial(\alpha_s^1)_r} & \frac{\partial \ddot{v}_r(1)}{\partial(\alpha_s^2)_r} & \cdots & \frac{\partial \ddot{v}_r(1)}{\partial(\alpha_s^m)_r} \\ \frac{\partial \ddot{v}_r(2)}{\partial(\alpha_s^1)_r} & \frac{\partial \ddot{v}_r(2)}{\partial(\alpha_s^2)_r} & \cdots & \frac{\partial \ddot{v}_r(2)}{\partial p(\alpha_s^m)_r} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial \ddot{v}_r(N_t)}{\partial(\alpha_s^1)_r} & \frac{\partial \ddot{v}_r(N_t)}{\partial(\alpha_s^2)_r} & \cdots & \frac{\partial \ddot{v}_r(N_t)}{\partial(\alpha_s^m)_r} \end{bmatrix}$$

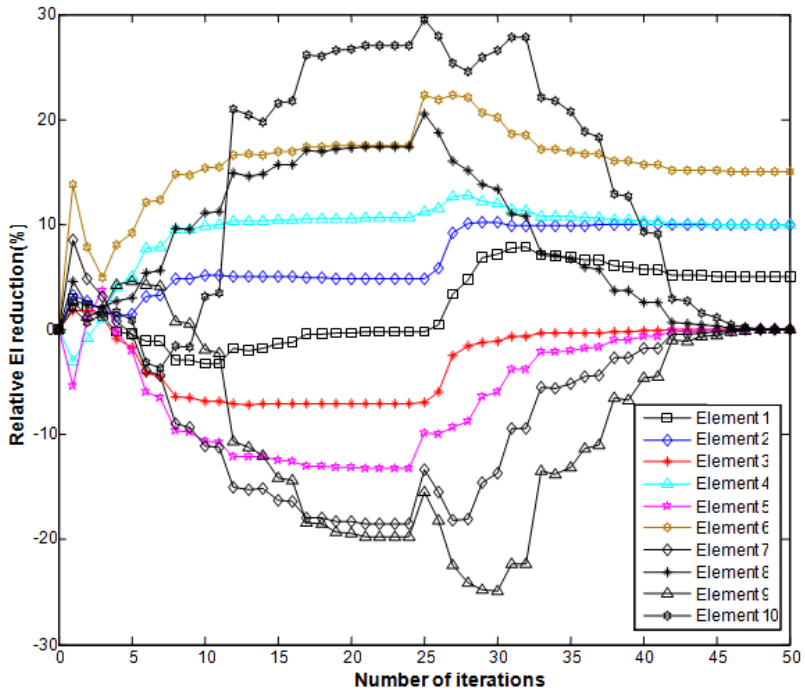
Indirect Bridge Structural Health Monitoring

Simulation Studies

- 30 m long beam divided into 10 Euler Bernoulli beam elements.
- Travel speed of vehicle is 20m/s.
- Sampling frequency is 200 Hz.
- All the measured data from the vehicle when it is on top of the bridge deck is used in the computation, i.e. 300 data.
- Study on (a) convergence property of the algorithm, (b) effect of vehicle model, (c) vehicle parameters, (d) different responses and (d) identification accuracy.
- Error is defined as the absolute value of relative error of the identified parameters, i.e.

$$AE = \sum_{j=1}^{m} \left\| \left(\left(\alpha_S^j \right)_{true} - \left(\alpha_S^j \right)_{identified} \right) / \left(\alpha_S^j \right)_{true} \right\|$$

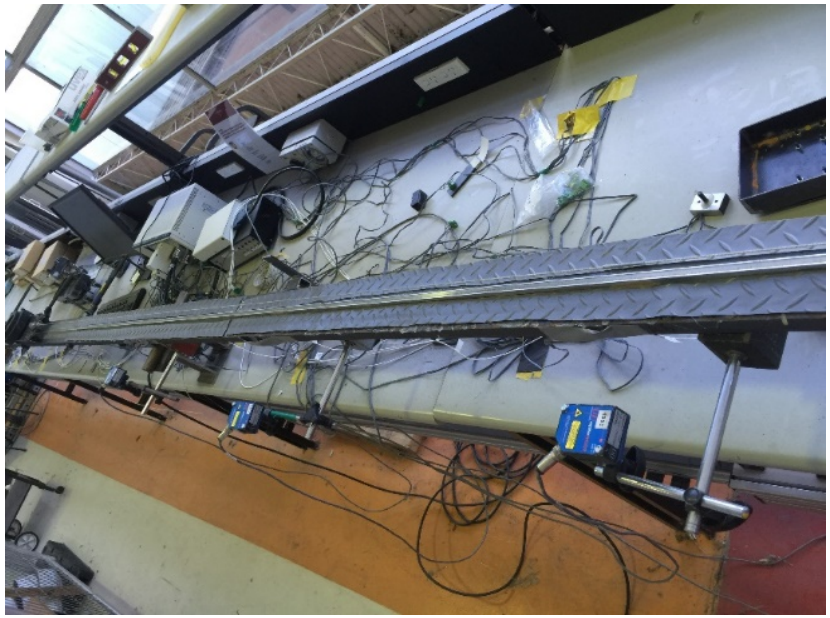
Indirect Bridge Structural Health Monitoring



Element number	True damage indices	Bu et al. (2006)		Zhu et al. (2014)
		$\ddot{y}_1$	$\ddot{y}_2$	$\mathbf{P}_{int}$
1	-5	-5.01	-4.95	-5.00
2	-10	-9.94	-10.01	-10.00
3	0	-0.13	0.00	0.00
4	-10	-9.85	-10.00	-10.00
5	0	-0.21	0.00	0.00
6	-15	-14.99	-15.00	-15.00
7	0	-0.17	-0.01	0.00
8	0	0.11	0.01	0.00
9	0	-0.07	-0.02	-0.00
10	0	0.05	0.04	0.00
Iteration number	-	41	37	50

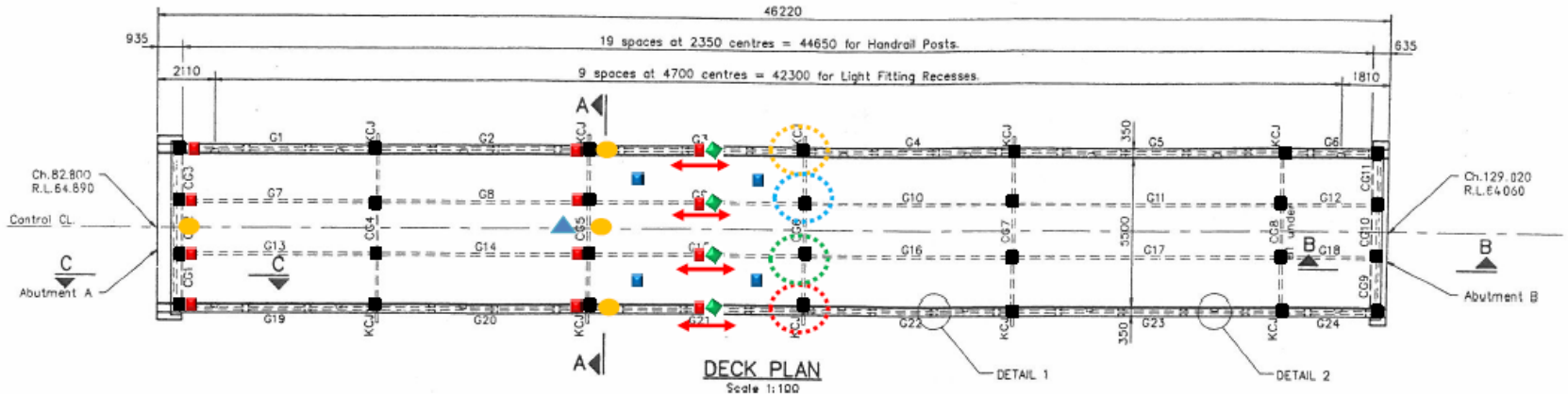
- A moving sensor in the form of a moving vehicle with two DOFs is employed for damage detection of the structure when it moves on top.
- The interaction force obtained from the vehicle responses is much more sensitive to local damages in the bridge structure than the acceleration response from the vehicle axle and body directly.

Indirect Bridge Structural Health Monitoring



Vehicle-bridge model in the lab

Field model(Collaboration with DATA61)



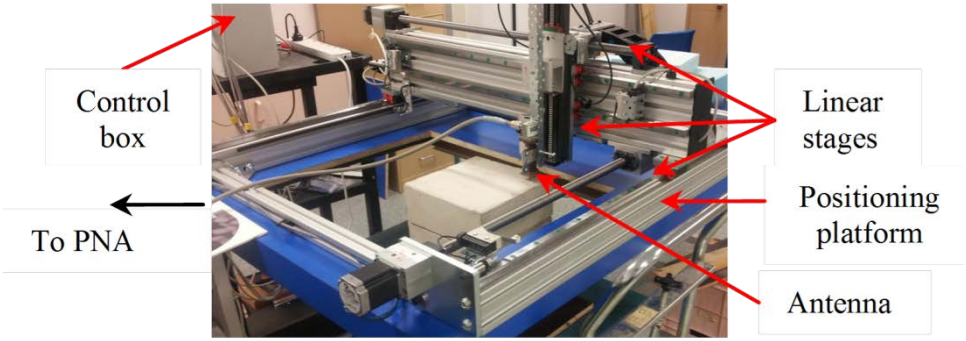
Conclusions and Recommendations

- **Direct bridge health monitoring with the instrumented bridge:** The direct approach is useful for monitoring a critical member of a bridge structure or evolution of a particular known damage condition, but with the disadvantages of intensive labour in sensor placement and maintenance. The lifespan of the sensory system is short relative to the lifespan of the monitored structure.
- **Indirect approach refers to data collection from sensors installed on vehicles crossing the bridge**: The instrumented vehicle can be used to have a quick scan on the large volume of highway bridges, and any suspected bridge will be monitored for a refined detection of the bridge damage.
- **Integrated approach:** Integrated with wireless sensor networks, the vehicle-bridge interaction can further be captured for more accurate bridge health monitoring.
- **Uncertainties in the vehicle-bridge interaction system:** 1) the effect of road surface roughness ; 2) the wheel-surface contact model.

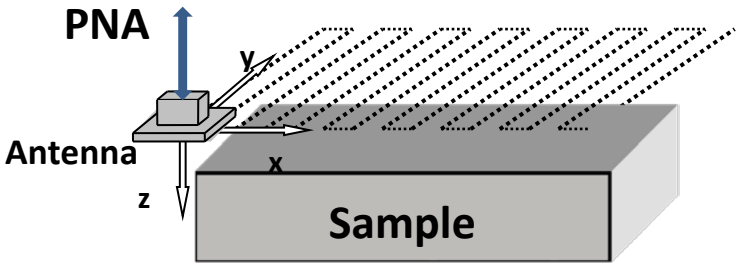
Sensor Technology Research

- Microwave and millimeter wave imaging
- Microwave embedded sensors
- Wireless RFID based sensory system
- Wireless power transfer in concrete

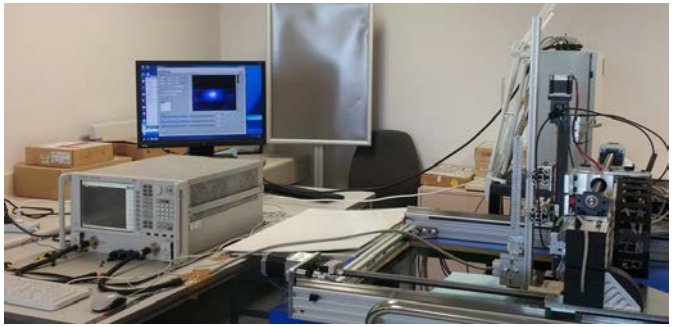
Multifunctional Imaging System



Scanning mechanism, antenna and concrete specimen



Raster scan



Multifunctional imaging system

Through plasterboard imaging

Picture of plasterboard wall

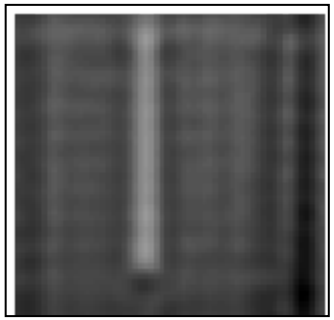
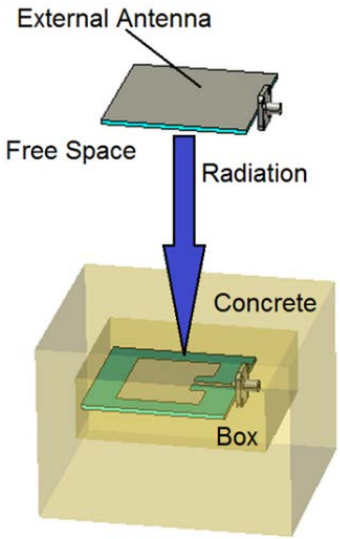


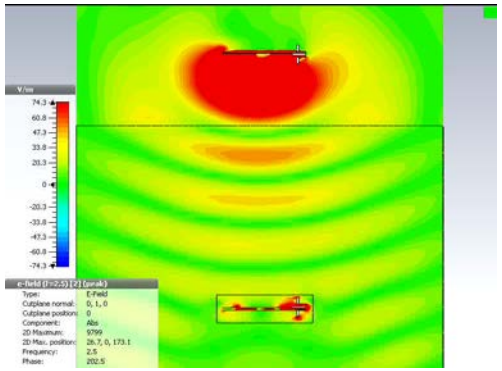
Image of 12-mm diameter steel rod under a plasterboard

Wireless Power Transmission in Concrete

Modelling and Simulation

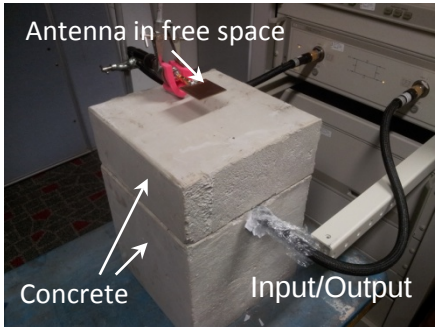


Electric field distribution



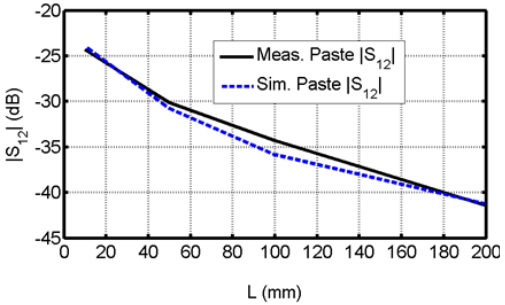
Measurement

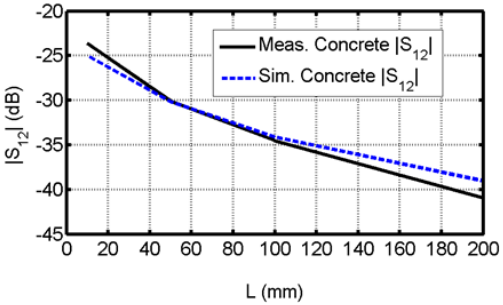
Manufactured embedded antenna module: Top and side view



Transmission coefficient

Fresh cement paste mimicking gel (20-mm thick top layer, ε_r = 38, σ = 1.6 S/m)

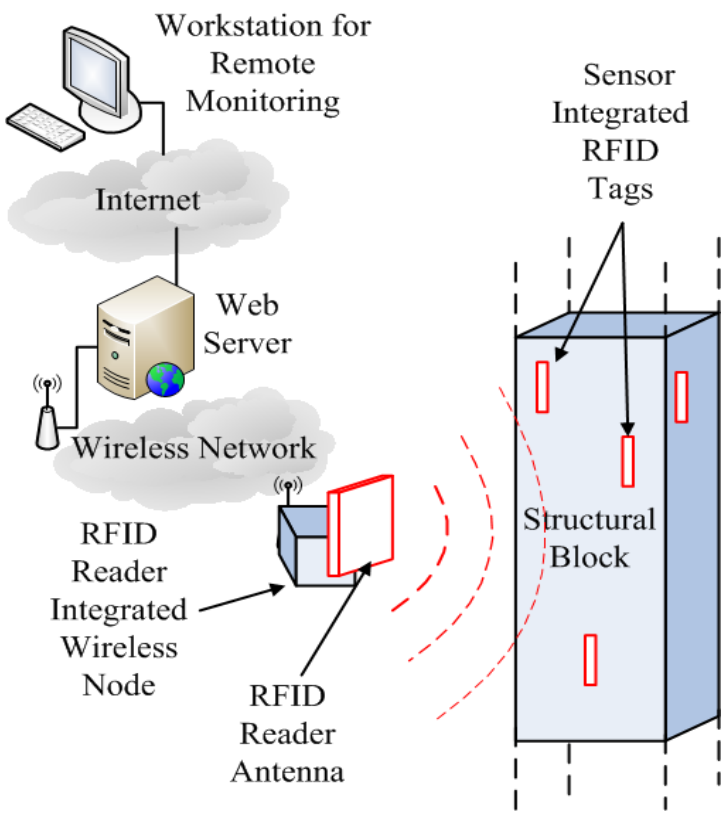




15-day-old concrete (125-mm thick top layer, ε_r = 4, σ = 0.102 S/m)

Wireless sensor integrated RFID tag system

Schematic of the proposed system



Advantages:

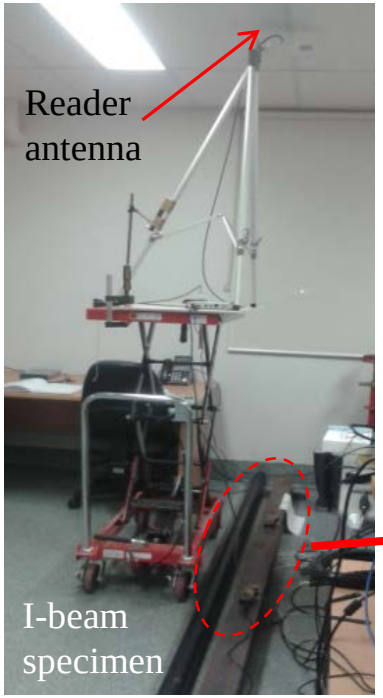
- The system is based on low cost, low power technology for health monitoring of large scale infrastructure
- Novel tag integrated antenna mountable on concrete and metal structures has been developed.
- It can be effectively integrated with sensors such as strain sensors and accelerometers to develop wireless multi-sensor system.
- Commercially available components such as RFID chips, microprocessor and reader can be used.

Current stage:

- Laboratory prototype integrating strain sensors and accelerometers has been built and tested

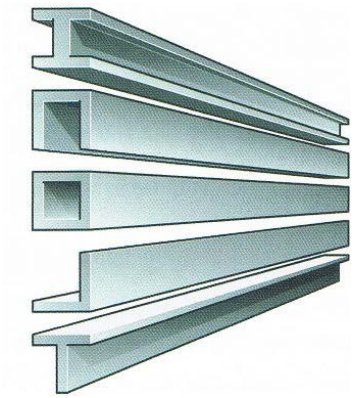
Design of the System and Measurement

Picture of the laboratory prototype testing I-beam

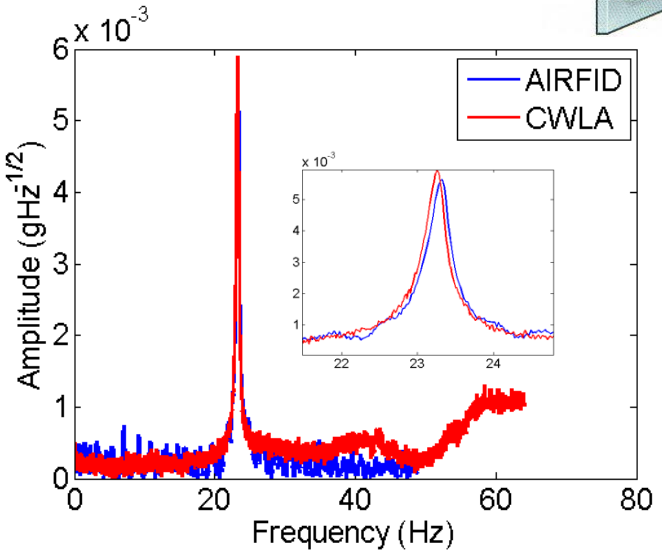


The developed RFID antenna

Accelerometer integrated RFID tag antennas



Measured acceleration



AIRFID – our system
CWLA – commercial system

Thank You!

Questions?