SHM of Buildings and Bridges: Research at QUT

From Theory to Application and Implementation

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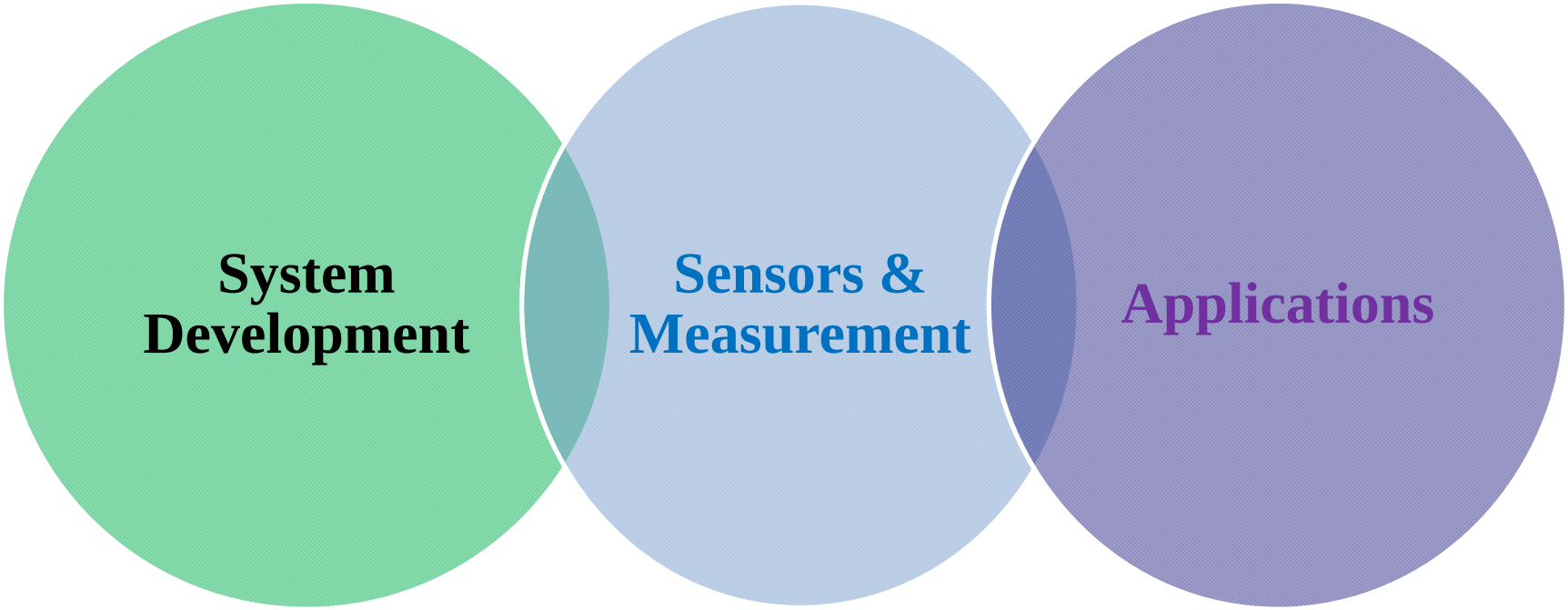
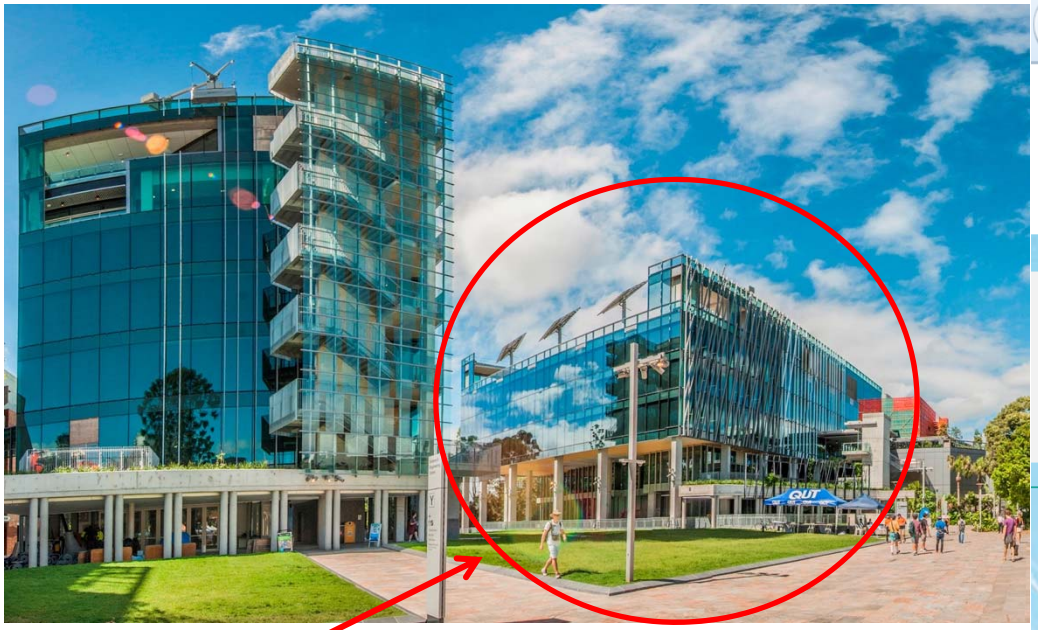

System Development
Sensors & Measurement
Applications

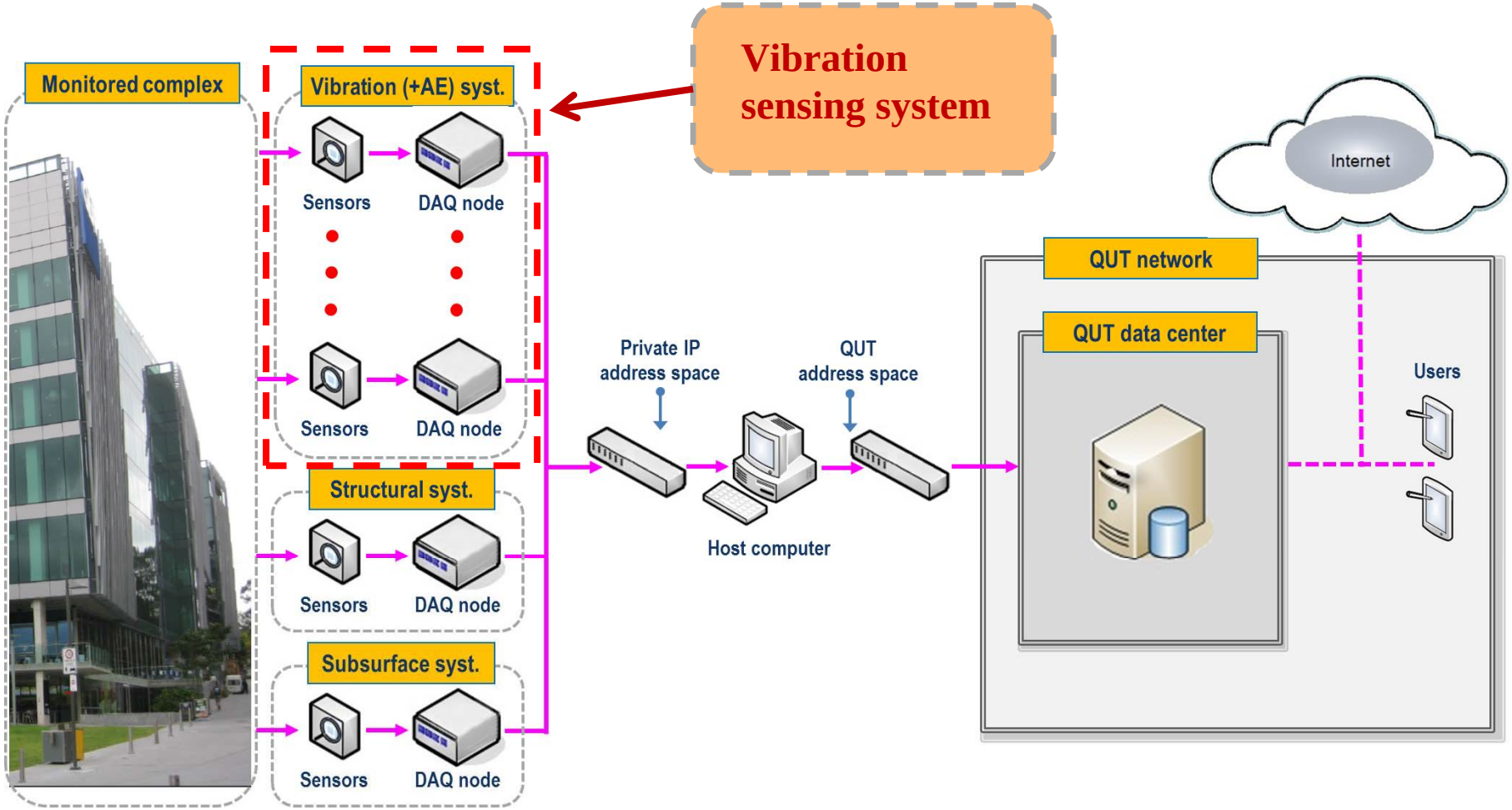
System Development

A real-world testbed



- P block
  - the main site for system deployment
- 3 systems: vibration (accel-based), structural (strain-based) & subsurface monitoring

Diagram of monitoring systems



AE: Acoustic Emission (with two sensors) sharing one DAQ with the accelerometers nearby

FBG-based displacement measurement

Methodology

Curvature approach

Curvature Measurement 2 pairs of FBG array

$$\kappa_i = \frac{\varepsilon_i^b - \varepsilon_i^t}{h}$$

Curvature data, k3

Curvature curve, K3

Vertical displacement function, D3

$$\iint \kappa \, dx \, dx$$

Inclination approach

Slope Measurement 5 FBG tilt sensors

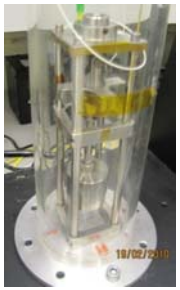
Slope data, s2

Slope curve, S2

Vertical displacement function, D2

$$\int \theta \, dx$$

Comparing with reference

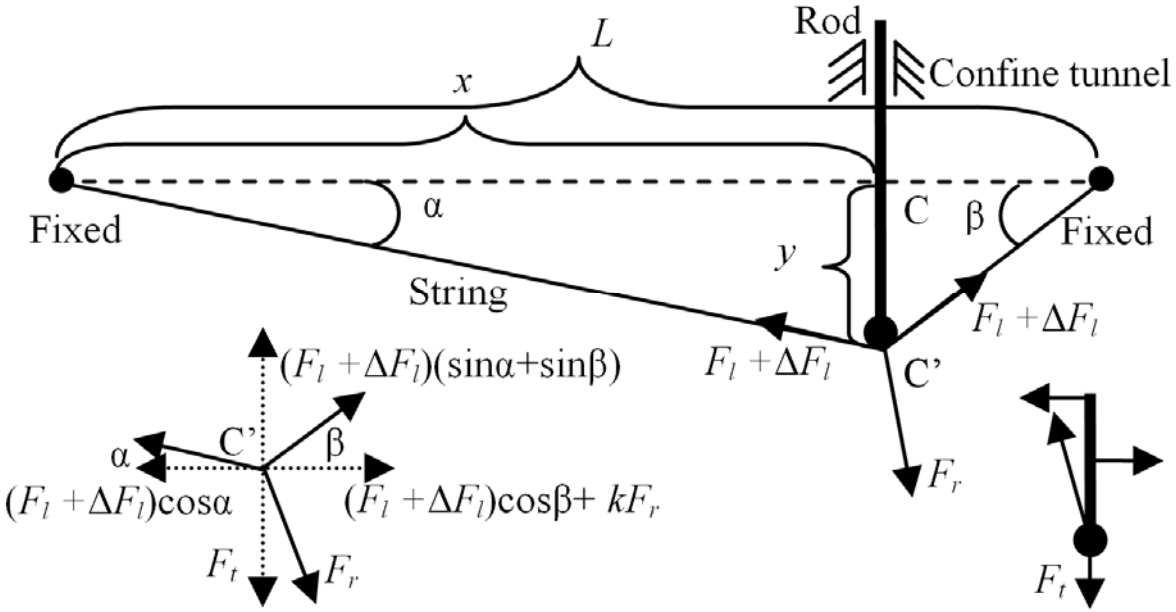


Interrogator, sampling of 1kHz

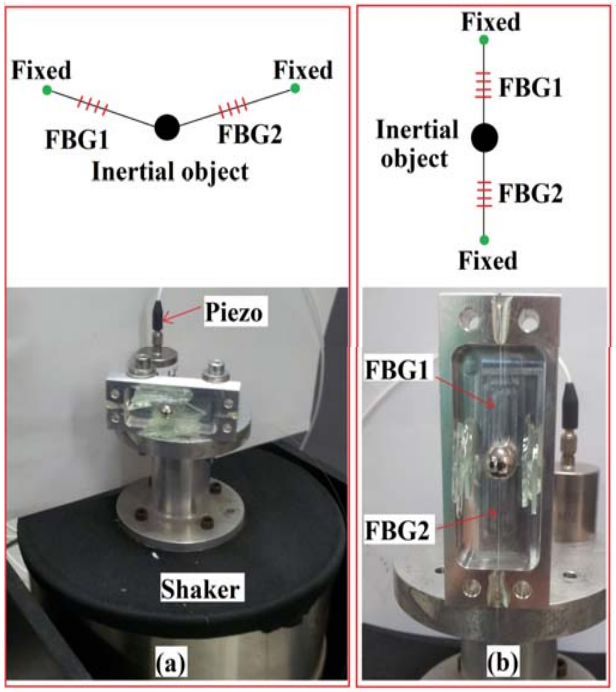
FBG: Fiber Bragg Grating

FBG-based accelerometer

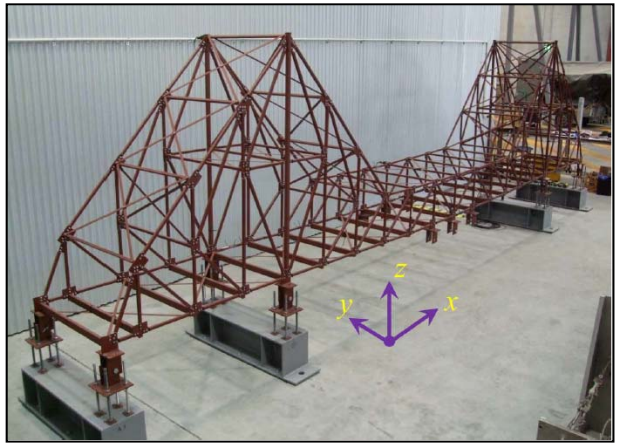
Theory of the nonlinear string transverse force amplifier

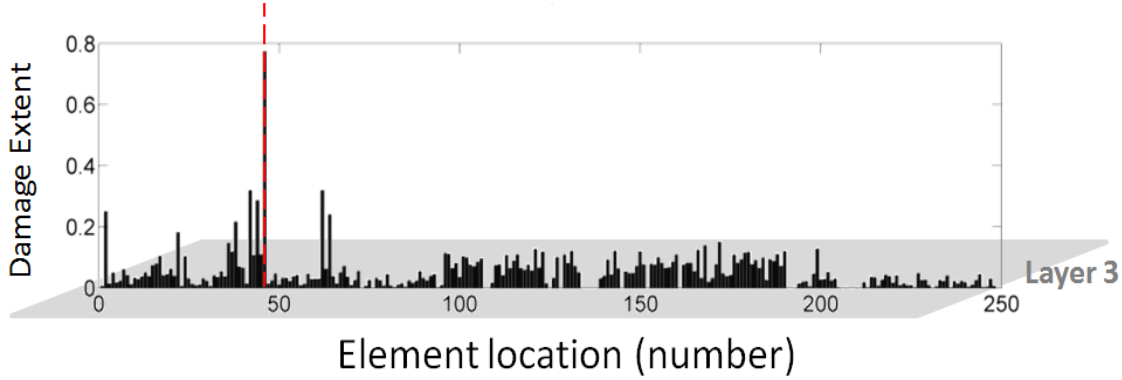


Biaxial FBG-based Accelerometer



- Multi-Layer Genetic Algorithm (ML-GA)





- Improved MSE indices for Flexural RC Members

Modification Function (MF1, MF2)

$$MF1(j,i)=\left|\frac{\varphi(j,i)}{\varphi(i)_{max}}\right| \qquad MF2(j,i)=\left|\frac{\varphi''(j,i)}{\varphi^{ii}(i)_{max}}\right|$$

Modal Sensitivity Value (MSV)

$$MSV(1,i)=\frac{\frac{\left\{\sum_{j=1}^{j=N}|\emptyset_d(j,i)|^2\right\}^{0.5}}{|\omega_d(i)|^2}-\frac{\left\{\sum_{j=1}^{j=N}|\emptyset_u(j,i)|^2\right\}^{0.5}}{|\omega_u(i)|^2}}{\frac{\left\{\sum_{j=1}^{j=N}|\emptyset_u(j,i)|^2\right\}^{0.5}}{|\omega_u(i)|^2}}$$

Improved MSE Indices

$$\beta 8_{(i)}(j,i)=[\beta 2(j,i)-1]\times MF1(j,i)$$

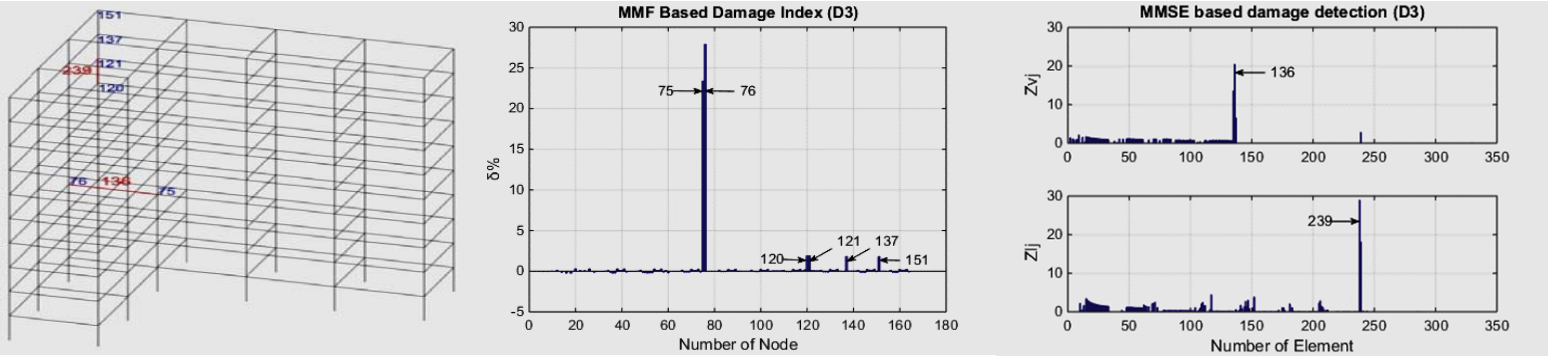
$$\beta 9_{(i)}(j,i)=[\beta 2(j,i)-1]\times MF2(j,i)$$

$$\beta 10_{c(1:M)}(j,1)=\frac{1}{M}\sum_{i=1}^{i=M}[\beta 8(j,i)-1]\times MSV(1,i)$$

$$\beta 11_{c(1:M)}(j,1)=\frac{1}{M}\sum_{i=1}^{i=M}[\beta 9(j,i)-1]\times MSV(1,i)$$

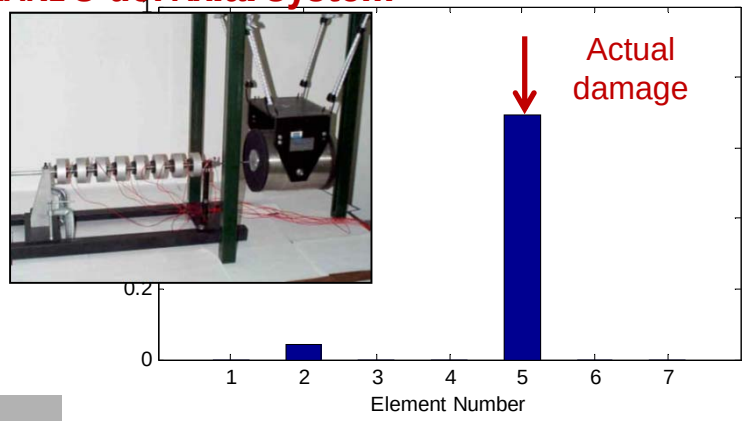
Applications

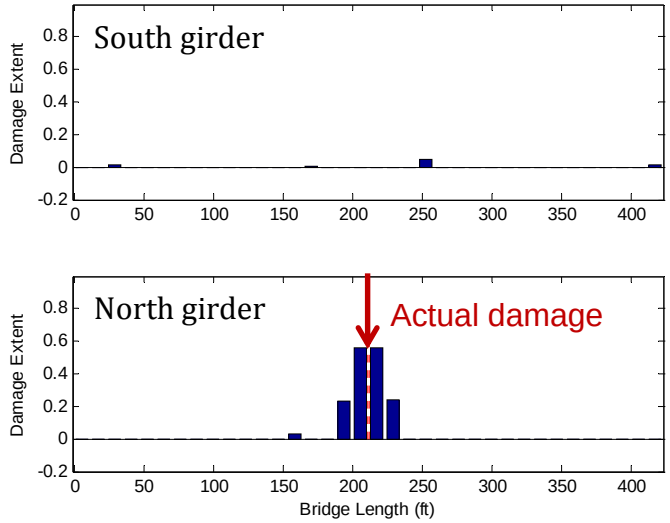
- VBDD using three-stage ANN and FRF data
- VBDD using Multi-Criteria Approach using MMF, MMSEL and MMSEV Multiple Damage (Element 136&239; node 75,76&120,121; 30%&30%)



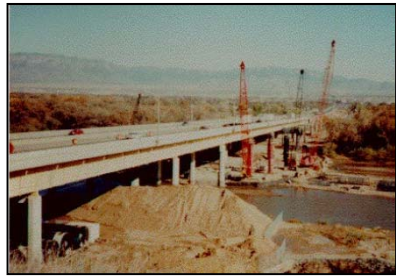
- VBDD using Ratio of Geometric MSE to Frequency

LANL 8-dof Axial System





I-40 Bridge, NM, USA

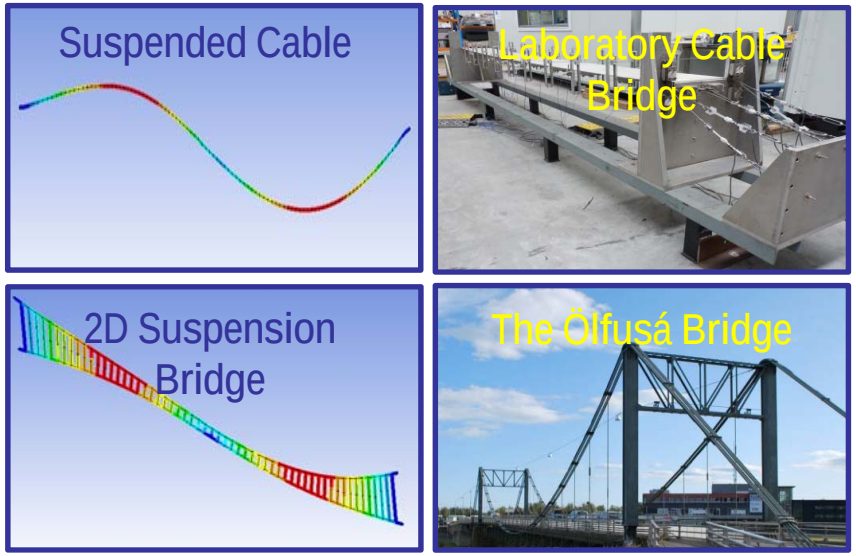


Applications

- Component Specific Modal Flexibility for Suspension Bridges

$$DI_V = \frac{\left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{DV} - \left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{HV}}{\left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{HV}}$$

$$DI_L = \frac{\left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{DL} - \left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{HL}}{\left[\sum_{i=1}^{m} \frac{1}{\omega_i^2} \phi_{xi} \phi_{xi}^T\right]_{HL}}$$



- VBDA for other structures
  - Concrete Gravity Dams
  - Arch Bridges

- Load Carrying Capacity Assessment of Highway Bridges
- Modal Analysis for complicated structures
- Model Updating
- Self-evaluation of Deterioration
- Identification for prestressing force in existing PC Bridges

Applications

Development of Self-evaluation of Deteroriation

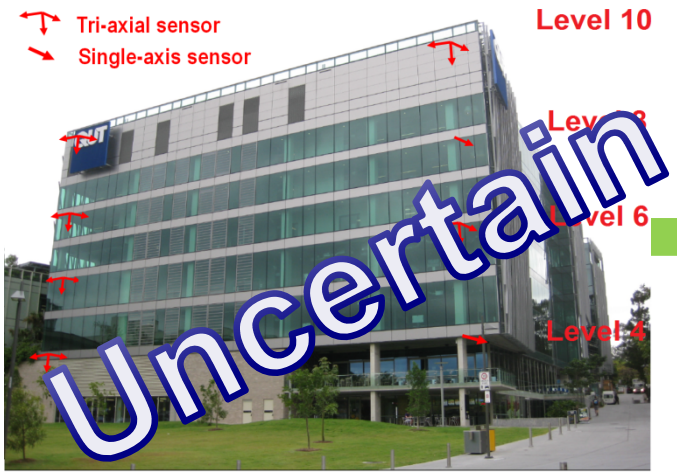
Model Updating

Deterioration Assessment

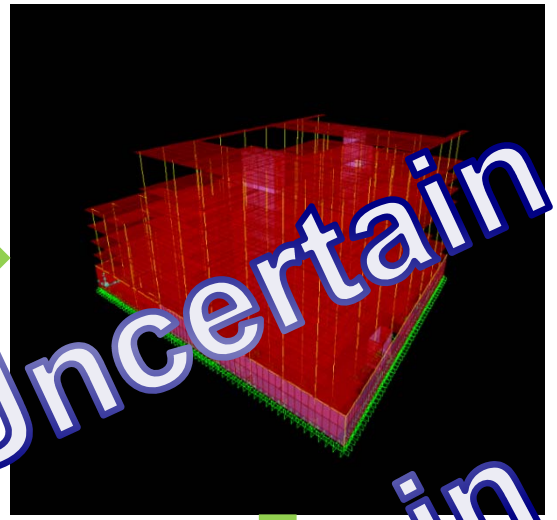
Identification of Prestressing for Existing Bridges

P-Block Structure; Model Updating

Conventional automated model updating



Set of Nominal Responses



Uncertain

Model Calibration

Set of parameters with nominal values

Calibrated Model

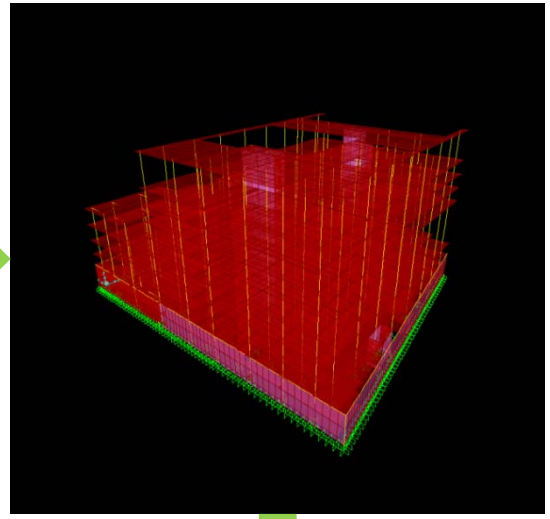
Hybrid model updating

P-Block Structure; Model Updating

Hybrid automated model updating

Include uncertainty

Set of Nominal Responses



Confidence values

Set of parameters with nominal values

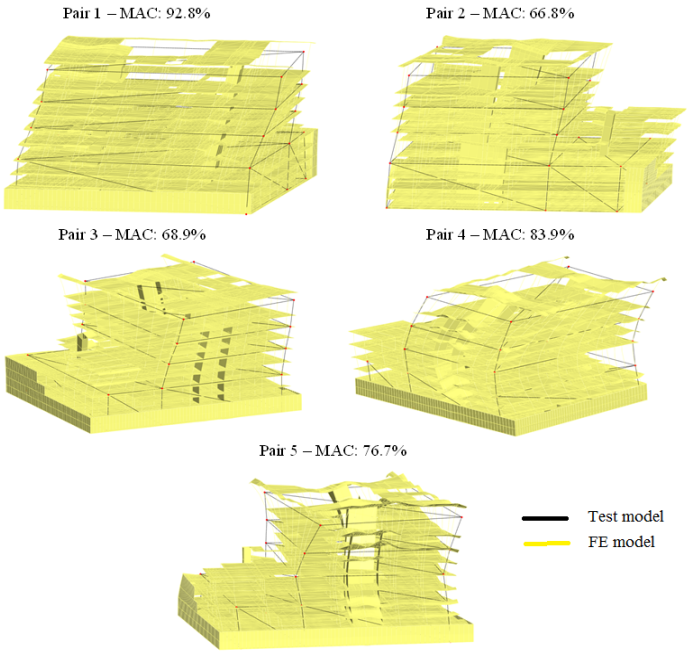
Model Calibration

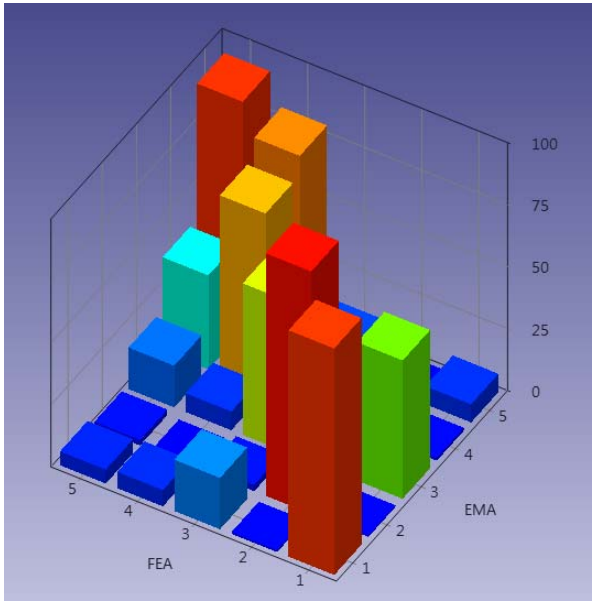
Calibrated Model

P-Block Structure; Model Updating

Conventional vs Hybrid Model updating results

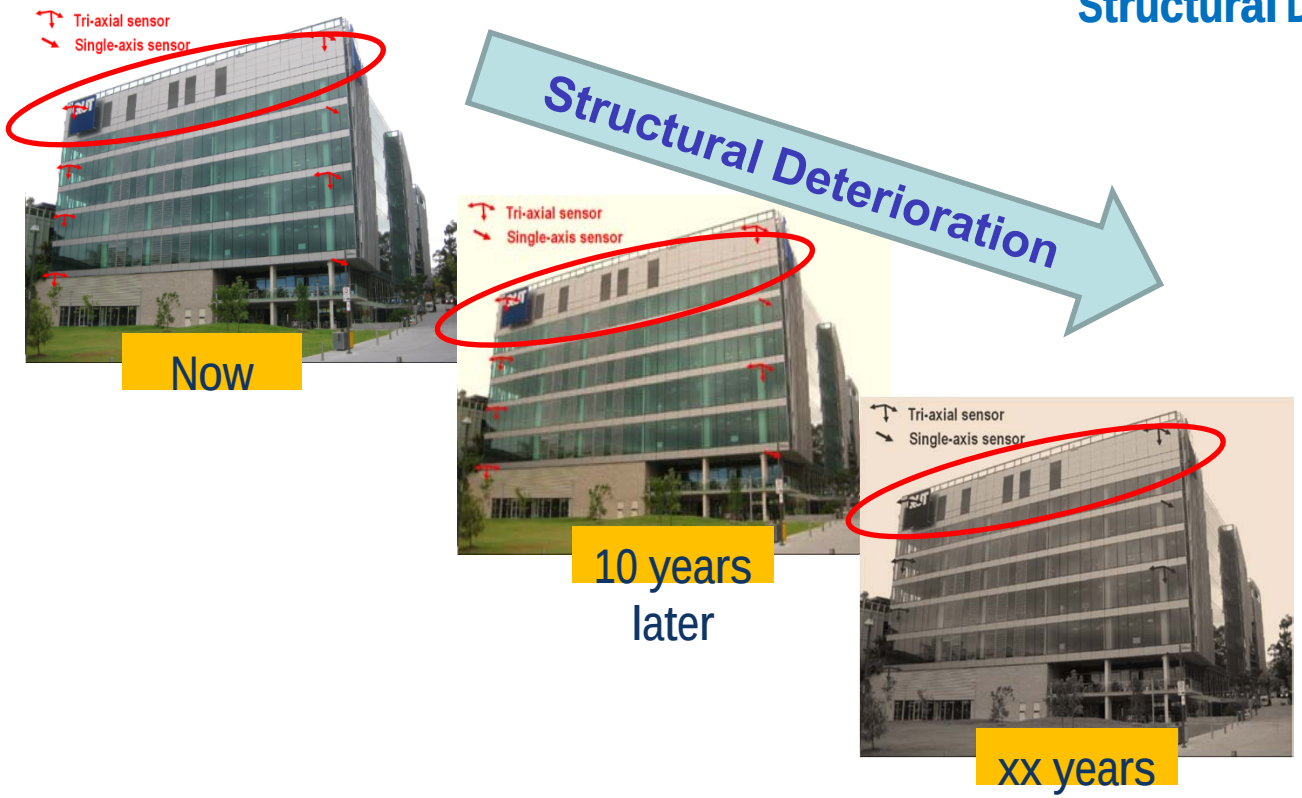
OMA Frequency	Initial FE model		Updated FE model –hybrid study		Updated FE model – conventional study	
	Frequency	Error	Frequency	Error	Frequency	Error
1.147 Hz	0.990 Hz	-13.69%	1.126 Hz	-1.83%	1.094 Hz	-4.62%
1.544 Hz	1.452 Hz	-5.96%	1.521 Hz	-1.49%	1.555 Hz	0.71%
1.653 Hz	1.678 Hz	1.51%	1.650 Hz	-0.18%	1.657 Hz	0.24%
3.989 Hz	3.680 Hz	-7.75%	3.977 Hz	-0.30%	3.988 Hz	-0.03%
4.254 Hz	4.972 Hz	16.88%	4.251 Hz	-0.07%	4.258 Hz	0.09%



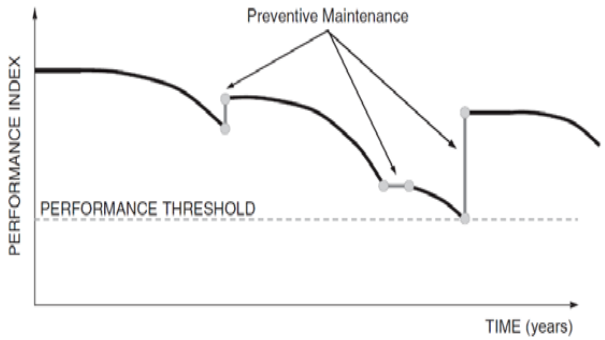


P-Block Structure; Deterioration Assessment

Structural Deterioration Assessment



The collapse building in Iowa (ABC9 NEWS)



Effect of deterioration on the structural performance (adopted from Frangopol and Soliman 2015)

Based on our initial investigations:
Long-term vibration feature data
+ statistical learning
can provide an answer

Time-Series Models

- Using a low-pass filter to cope with high frequency content

Optimum model order

- *Model fit*: be *generalized* to a wide range of data sets at the same health state
- *Model complexity:* be *higher enough* to capture the vibration characteristics of structures

Detecting Deterioration:

$$\boldsymbol{D}^{i}_{3X1} = \boldsymbol{B}^{i}_{3X1} - \overline{\boldsymbol{B}^{H}_{3X1}}$$

$$FR^{i} = \sqrt{{D_1}^2 + {D_2}^2 + {D_3}^2}$$

$$DI^{i} = \frac{\left|FR^{i} - \overline{FR^{H}}\right|}{\overline{FR^{H}}}$$

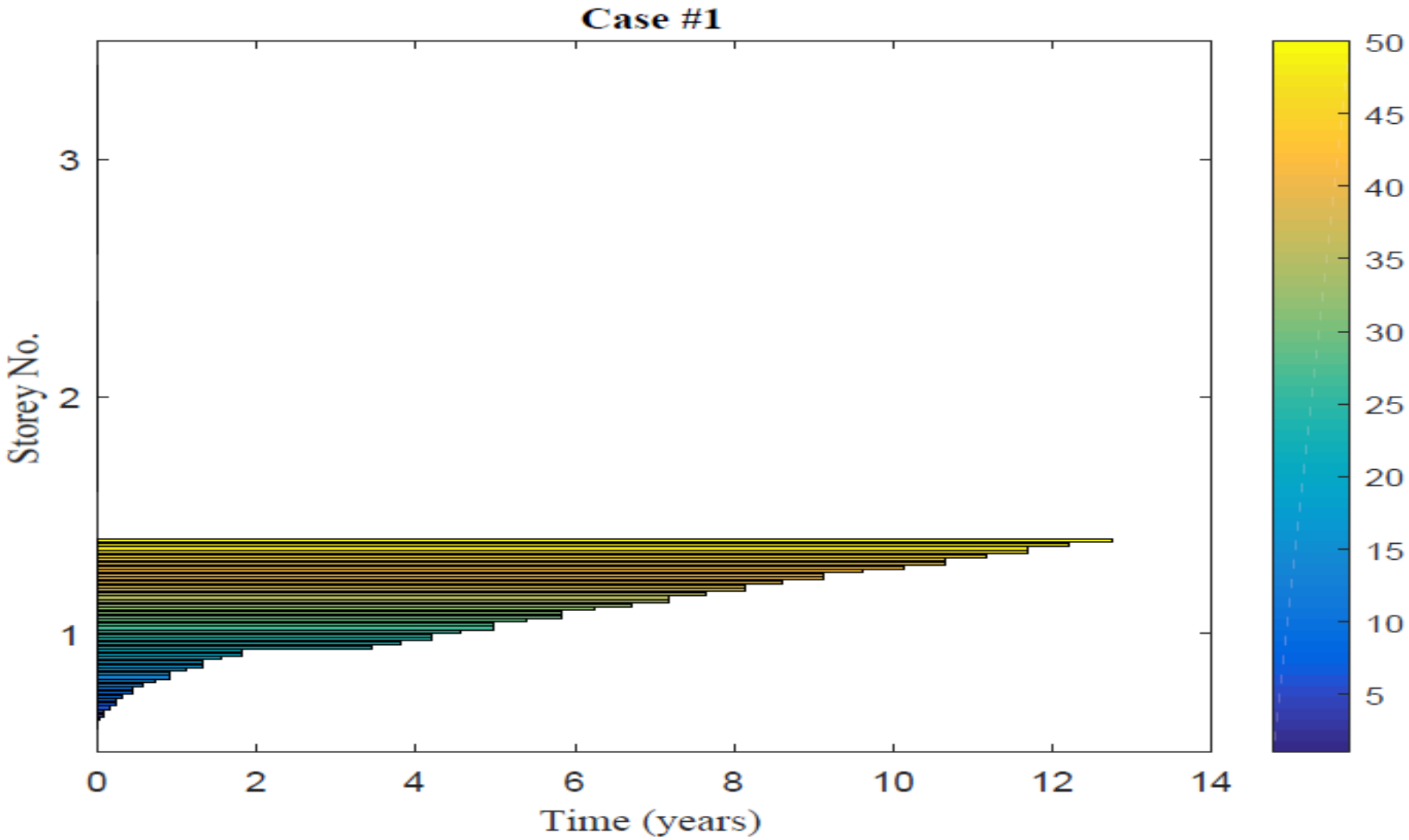
Locating Deterioration:

$$f = \frac{(\mu_i - \mu_H)^2}{\sigma_i^2 + \sigma_H^2}$$

$$F_j = normalized(f)$$

$$G_j = F_j - \frac{(\Sigma_{i=1}^{n} F_i) - F_j}{n-1} \geq 0$$

P-Block Structure; Deterioration Assessment



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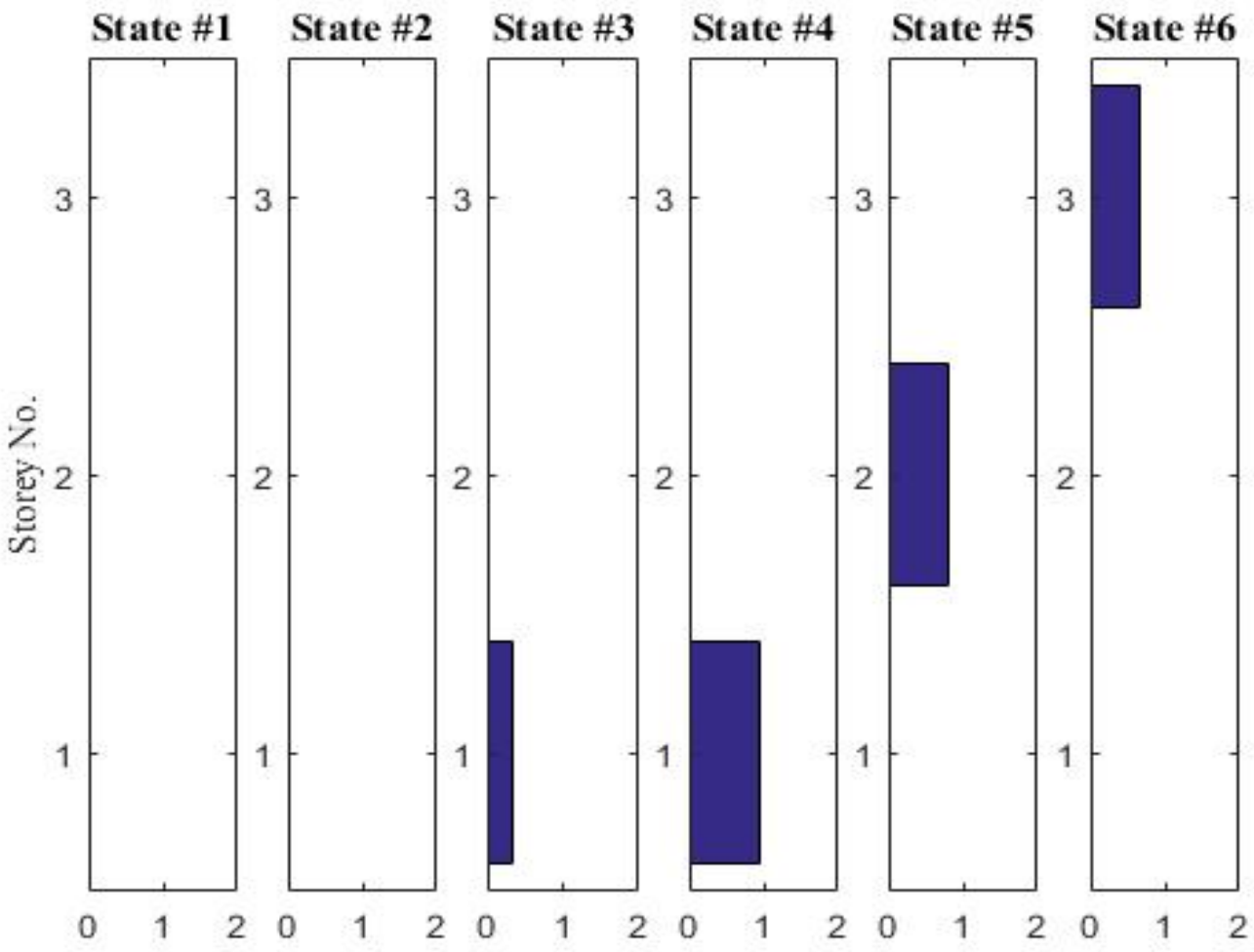
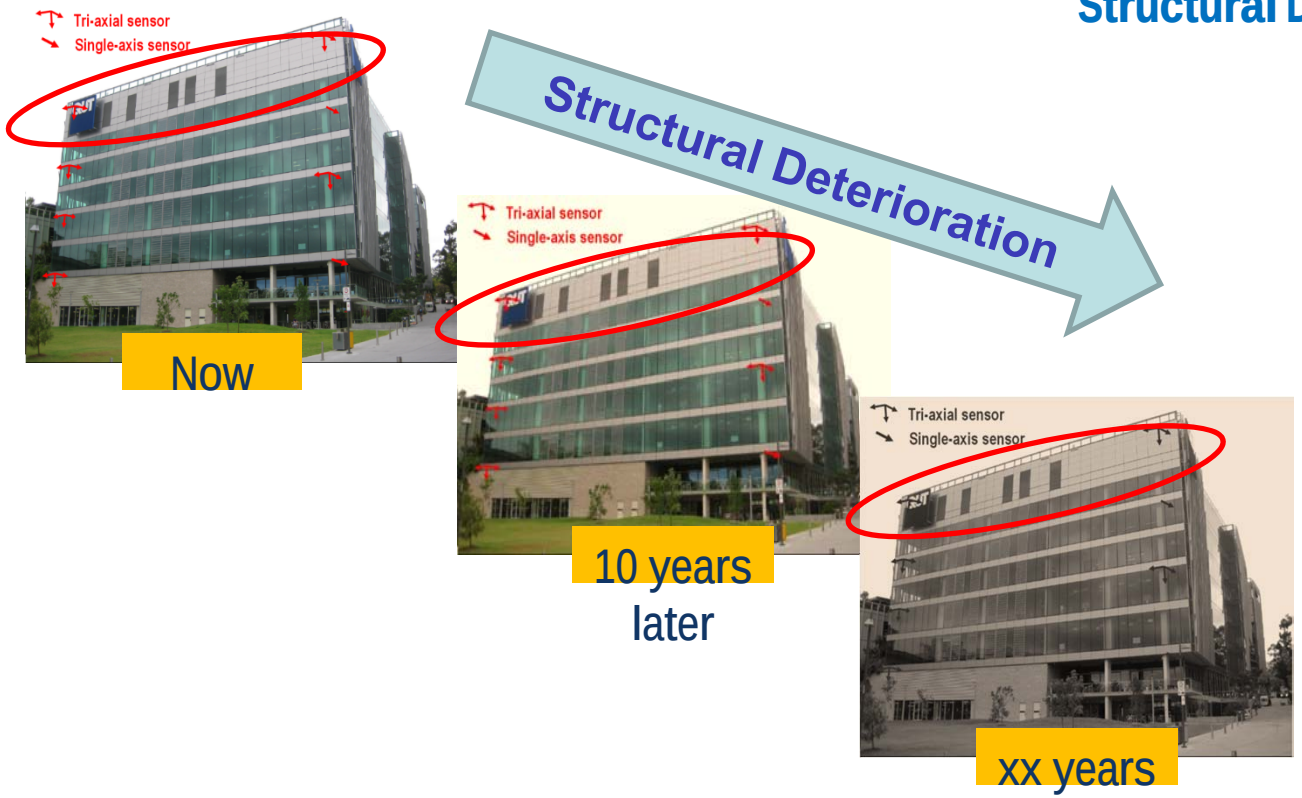


P-Block Structure; Deterioration Assessment

Structural Deterioration Assessment



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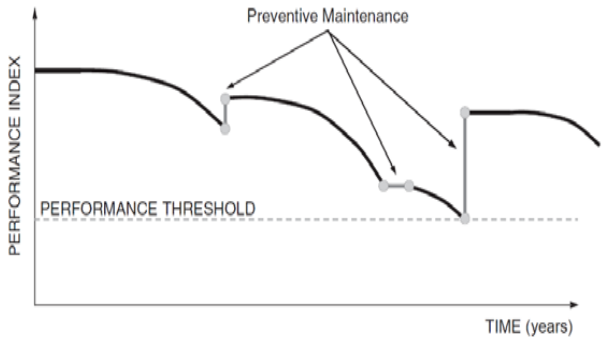

Effect of deterioration on the structural performance (adopted from Frangopol and Soliman 2015)

Based on our initial investigations:
Long-term vibration feature data
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can provide an answer

Applications

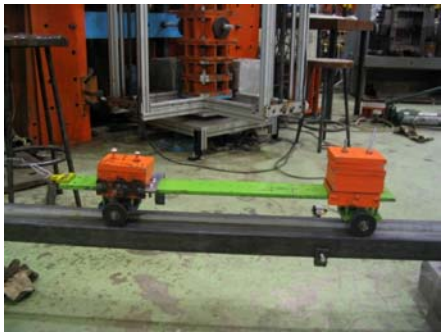
Development of Self-evaluation of Deteroriation

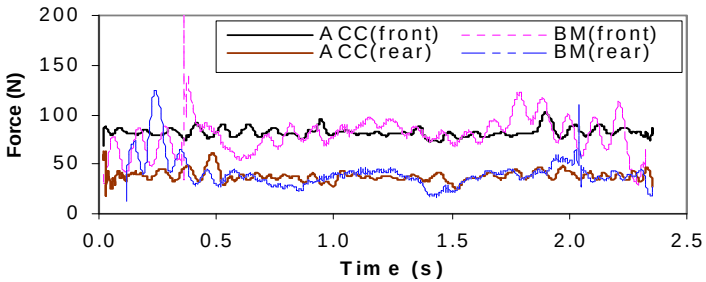
Model Updating

Deterioration Assessment

Identification of Prestressing for Existing Bridges

B6. Force Identification for prestressing tendon/bridge cable





The project aims to develop various methods to identify prestressing forces by:

- ✓ Using MFI methods
- ✓ Using VBDI methods
- ✓ Non-destructive testing techniques such as EMAT

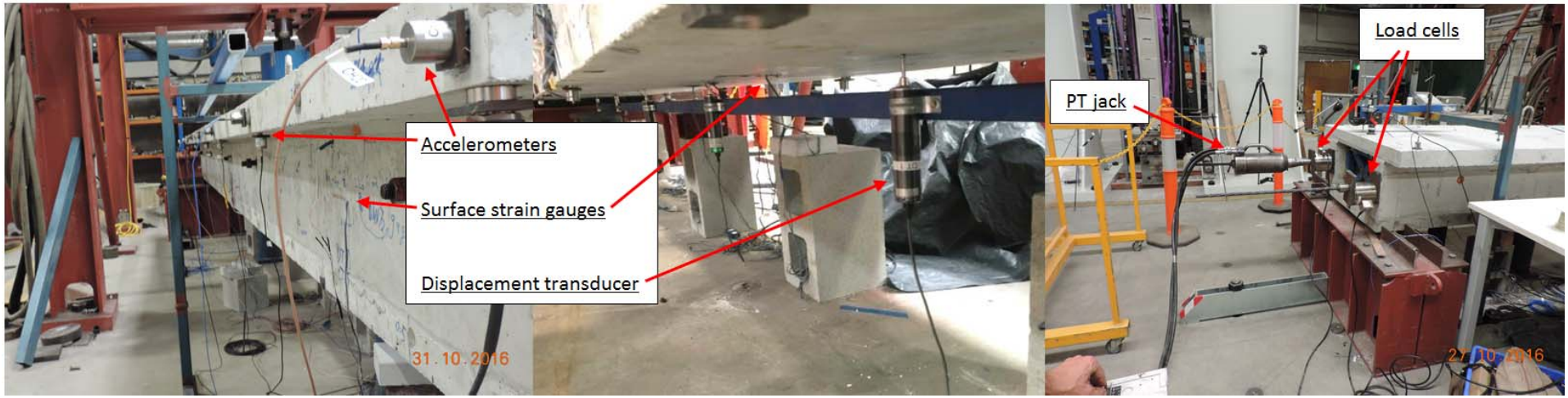
Intended to be validated with real highway/pedestrian bridges such as Neville Hewitt bridge in Rockhampton (pictured) and V-Z link bridge at QUT

MFI: Moving Force Identification; VBDI: Vibration Based Damage Identification; EMAT: Electromagnetic Acoustic Transducers

Prestress Force Identification of Box Girder Bridges

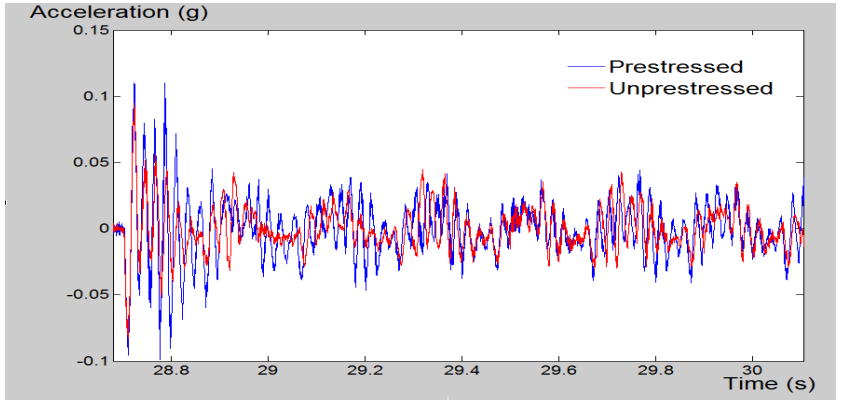
Construction of Lab model

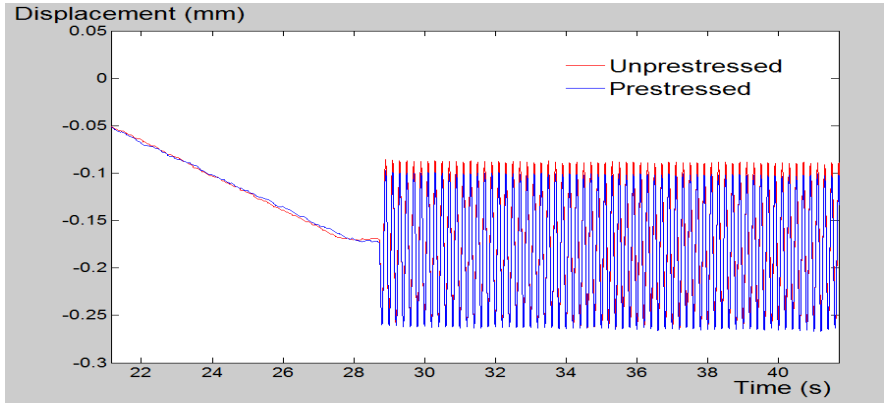
Instrumentation



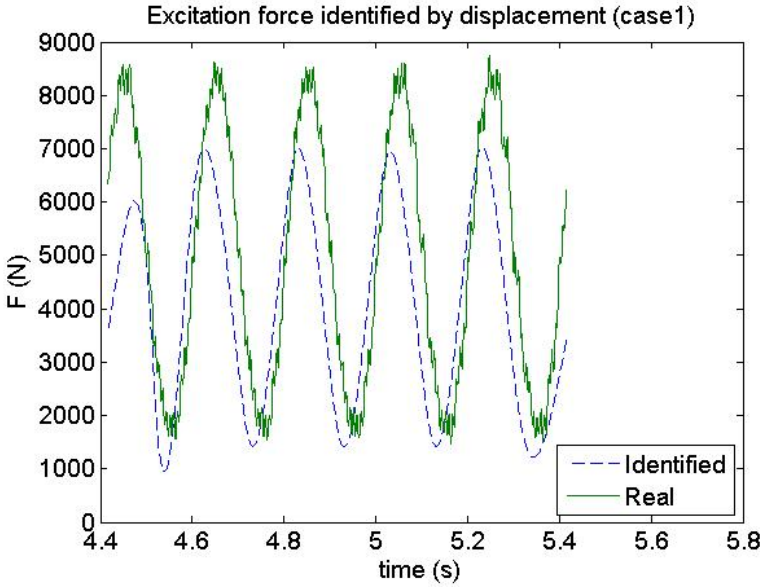
Prestress Force (PF) Identification of Box Girder Bridges

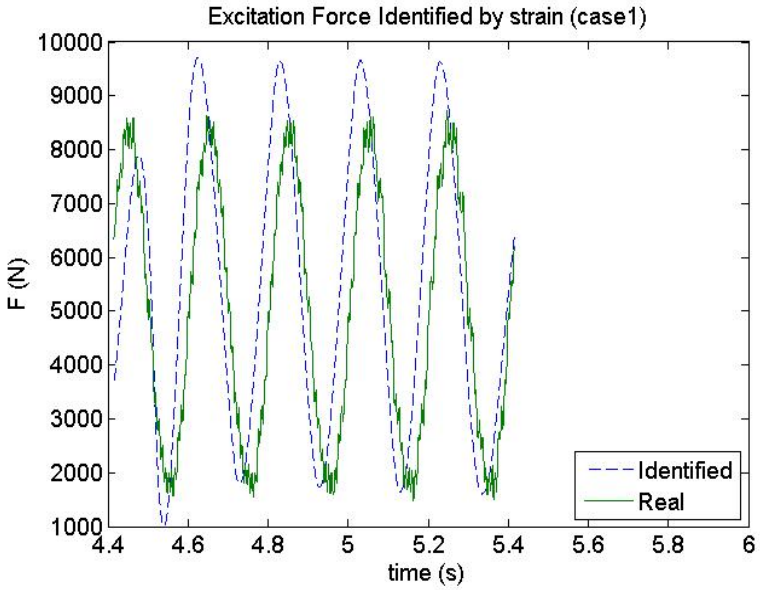
Measured responses





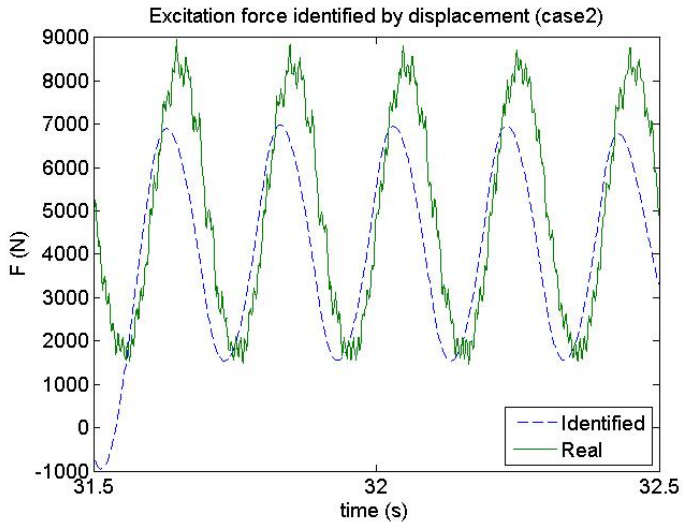
Synergic Identification of Excitation and PF

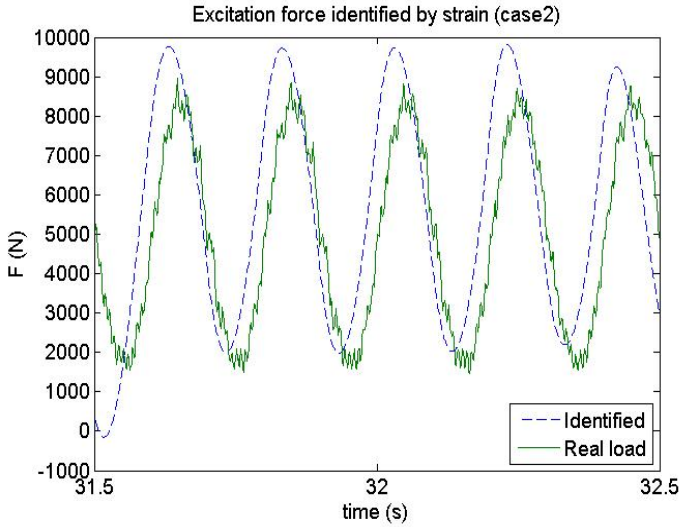


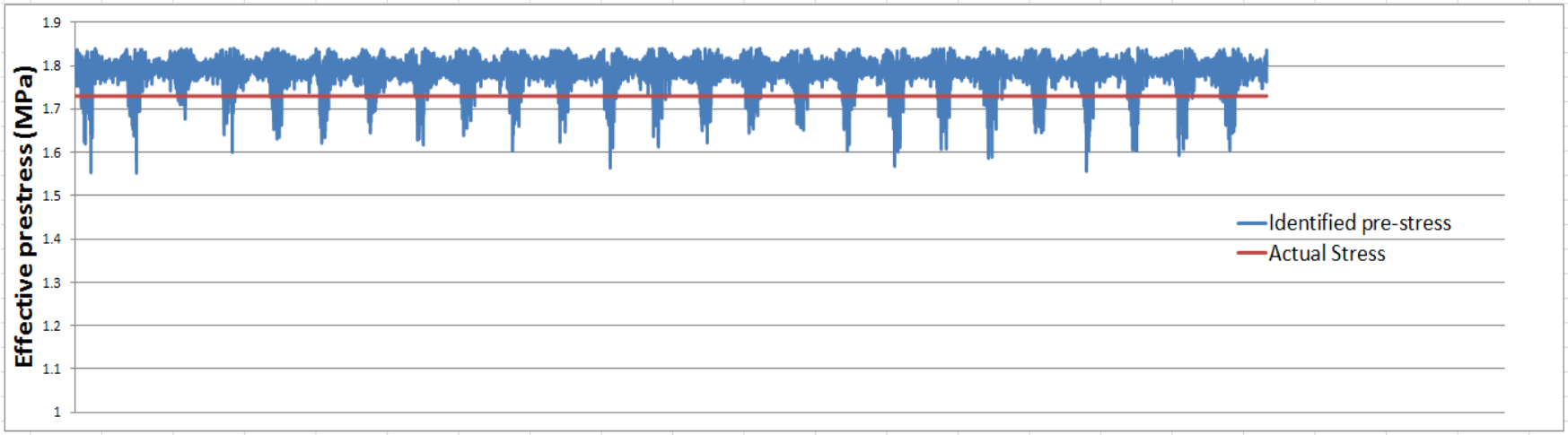


Prestress Force (PF) Identification of Box Girder Bridges

Synergic Identification of Excitation and PF (cont.)

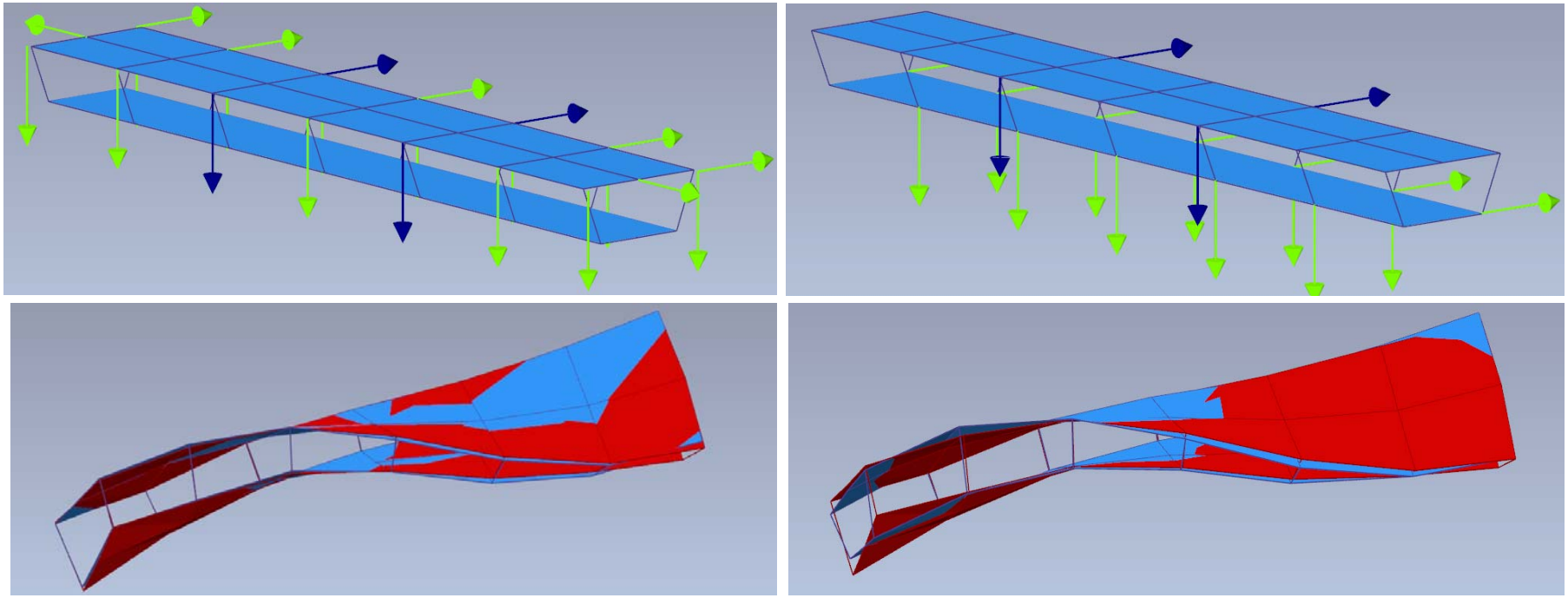






Prestress Force Identification of Box Girder Bridges

Impact of PF change on modal parameters



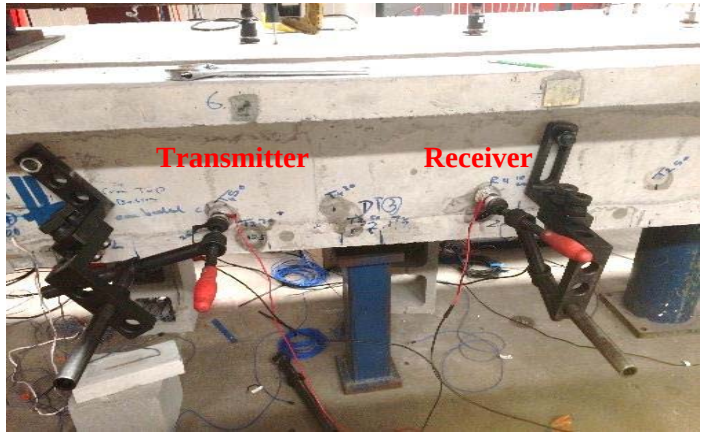
Within detectable modes (~10 modes):

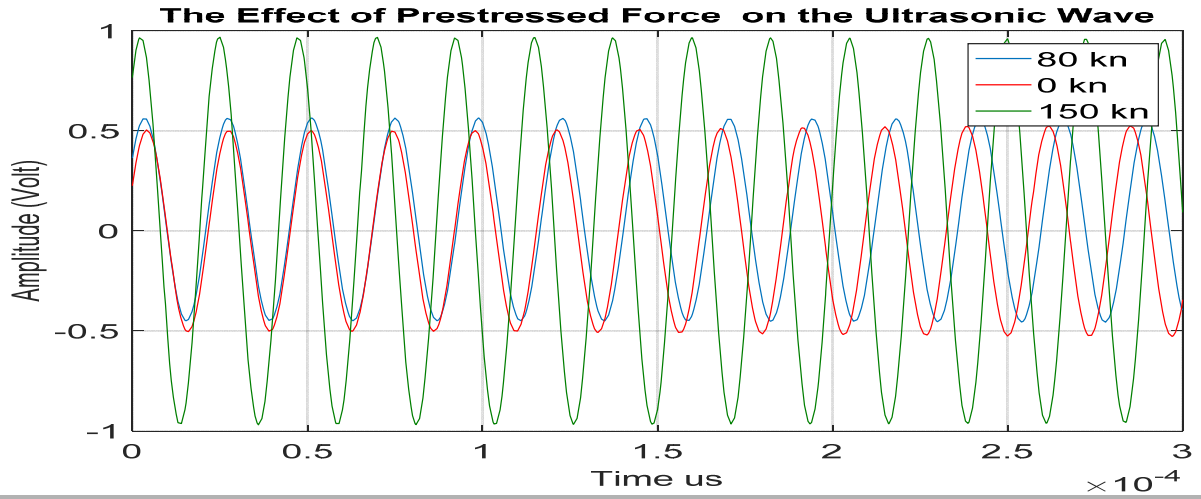
- **Mode shape change: max 13% and consistent with PF change**
- **Frequency change: no larger than 2%**

Mode shape change is a better indicator for PF change

Prestress Force Identification of Box Girder Bridges

Impact of PF on ultrasonic wave amplitude and velocity





Summary

System Development

- Developed a semi-complete data synchronization scheme.
- Established and evaluated a handy and synchronization-effective SHM-oriented WSN.
- Established and updated finite element models with measured modal data.
- Examined performance of the structure/SHM system under earthquakes.
- Developing a real time SHM system for post-disaster decision support.

Sensors/ Measurement

- Developed two FBG-based vertical displacement measurement methods using curvature and inclination approaches.
- Developed new FBG accelerometers using axial and/or transverse force amplifiers.

WSN: Wireless Sensor Network; FBG: Fibre Bragg Grating

Summary

Applications (On-Going)

- VBDD Methods for the following structures have been developed and further improvements are under investigation:
  - Truss Bridges
  - Slab-on-girder bridges
  - Multi-storey buildings
  - Suspension Bridges
  - Concrete Gravity Dams
  - Arch Bridges
  - Asymmetric High Rise Buildings
- Load Carrying Capacity Assessment of Highway Bridges
- Modal Analysis and Model Updating
- Deterioration Assessment
- Prestressing Force Identification for existing bridges

MSE: Modal Strain Energy; MF: Modal Flexibility; PSC: Prestressed Concrete; EMAT: Electromagnetic Acoustic Transducer

Thank you for your attention!

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