SHM of Buildings and Bridges: Research at QUT

From Theory to Application and Implementation

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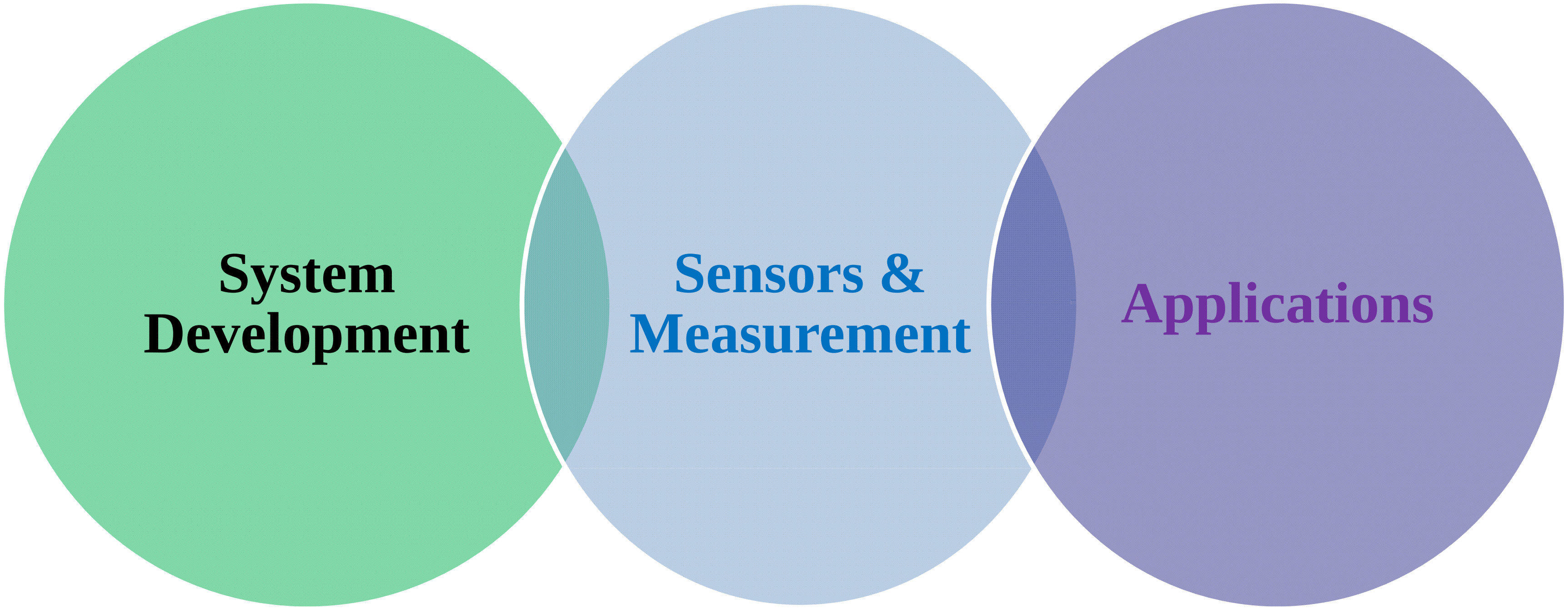
Structural Health Monitoring (SHM) research at **QUT** - **Introduction**



SHM research at **QUT** - **Research Aims**

System Development

- Integrating available sensing technologies into synthetic sensing systems
- Assessing & mitigating major sensing uncertainties on SHM outcomes

Sensors/ Measurement

- Developing New Sensing/Measurement Techniques
- Exploring New Methodologies To Make Use Of Sensors

Applications

- Developing Vibration-Based Damage Identification techniques for building and bridges
- Developing Structural Rating methods for railways bridges

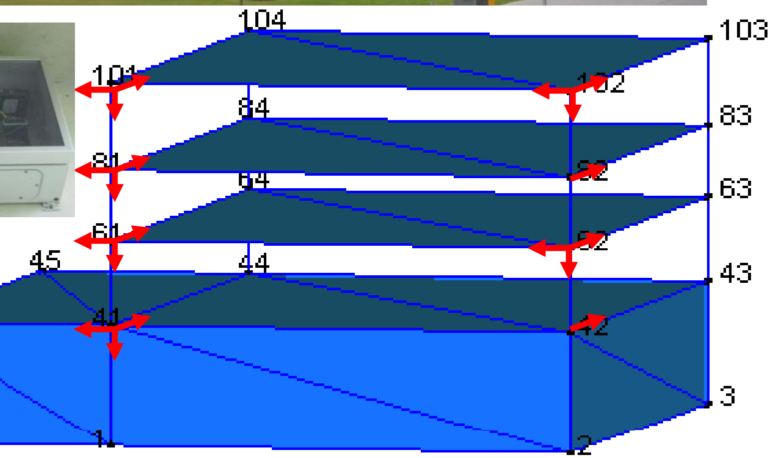
1. **QUT SHM test-bed; Building SHM syst. (cont.) & Footbridge SHM syst.**

2. **Effects of Data Synchronization Error (DSE) on Output-only Modal-based Damage Identification (OMDI)**

3. **Experimental modal analysis of QUT Bridge Model using a global multi-layer-hybrid optimisation method.**

SHM research at **QUT** - **System Development**

1. QUT SHM test-bed



Building SHM syst.

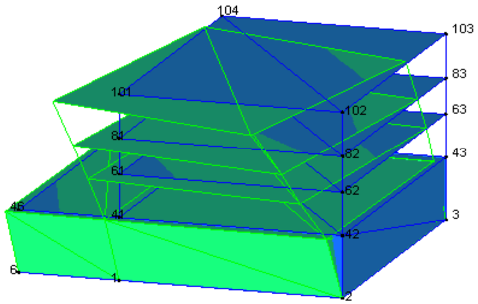
- Sensors located at L4, 6, 8 & 10
- Sensor sensitivity: 2V/g
- Embedded data acquisition using NI cRIO : To accommodate broadly distributed sensors (also as for strain gauges, soil pressure sensors, etc)
- Each sensor (in small enclosure) connected to one cRIO (glass box)
- TCP/IP command-based solution: initial data synchronisation errors reduced to ~ 0.3 to 0.5 millisecond
- Initially sampled @ 2kHz, decimated to 100Hz

Building SHM syst. (cont.)

- Unmeasured DOFs computed from measured ones of the same level based on theory of rigid body of slab
- At least 7 modes excited by ambient excitation (wind, human activities...)
- Modes estimated by Output-only Modal Analysis techniques
- Mode shape animation examples: mode #1, mode #4 & mode #7

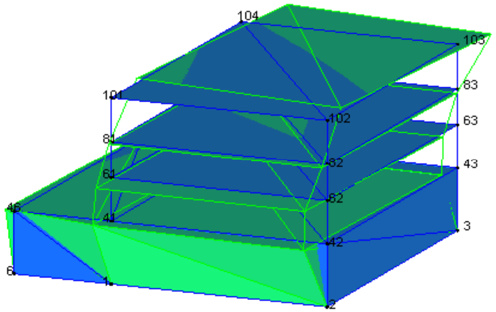
Mode #1

1.15 Hz



Mode #4

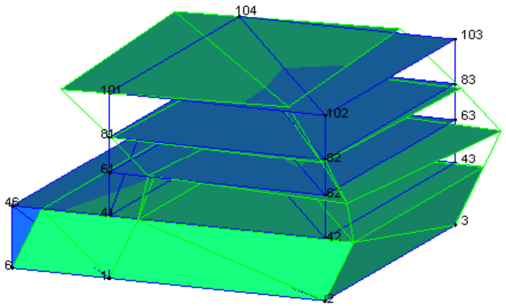
3.99 Hz



QUT

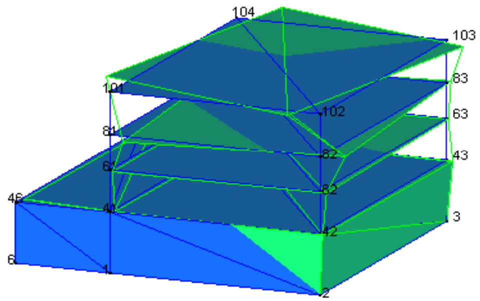
Mode #6

4.91 Hz



Mode #7

6.53 Hz



SHM research at **QUT** - **System Development**

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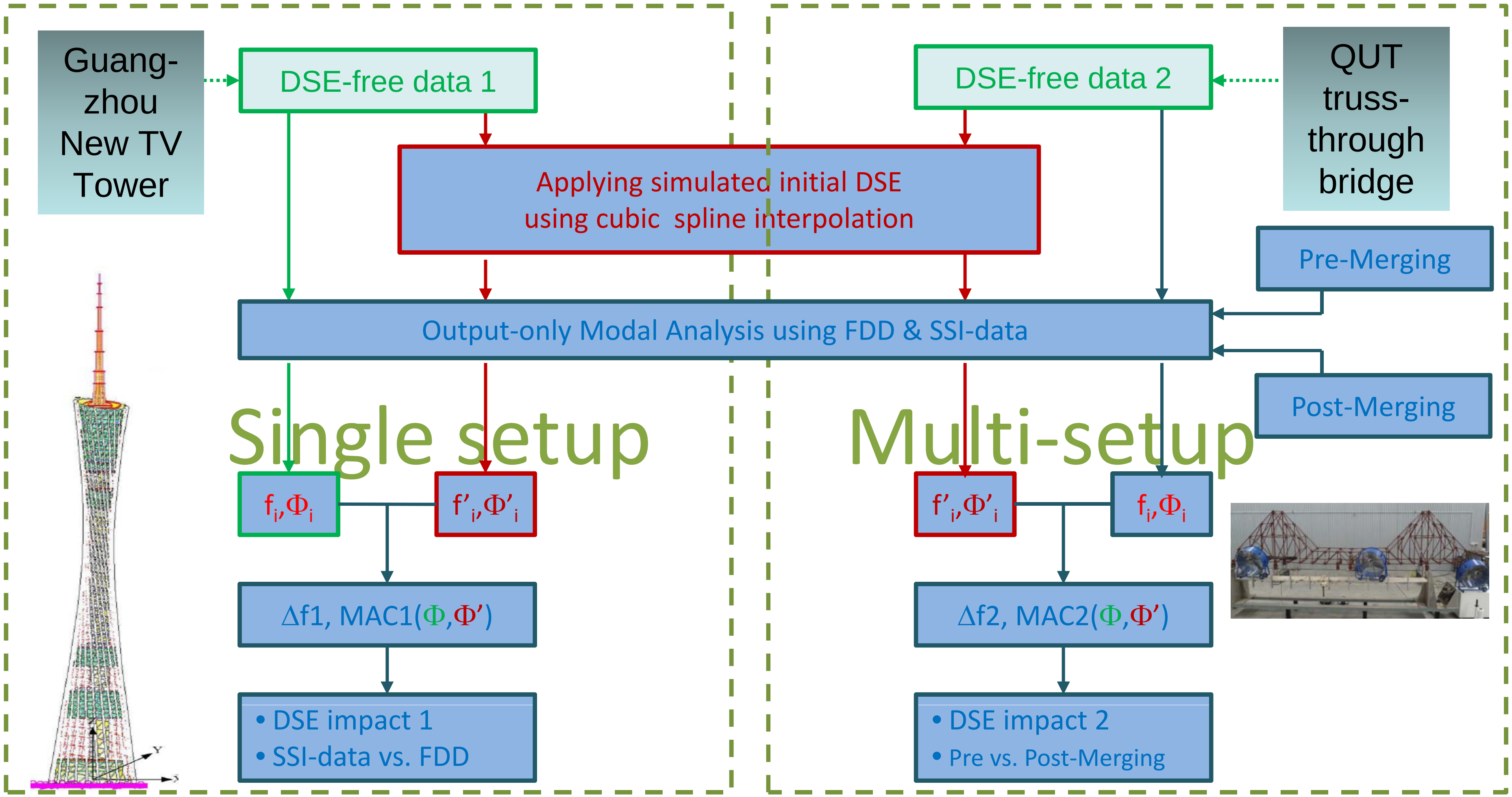
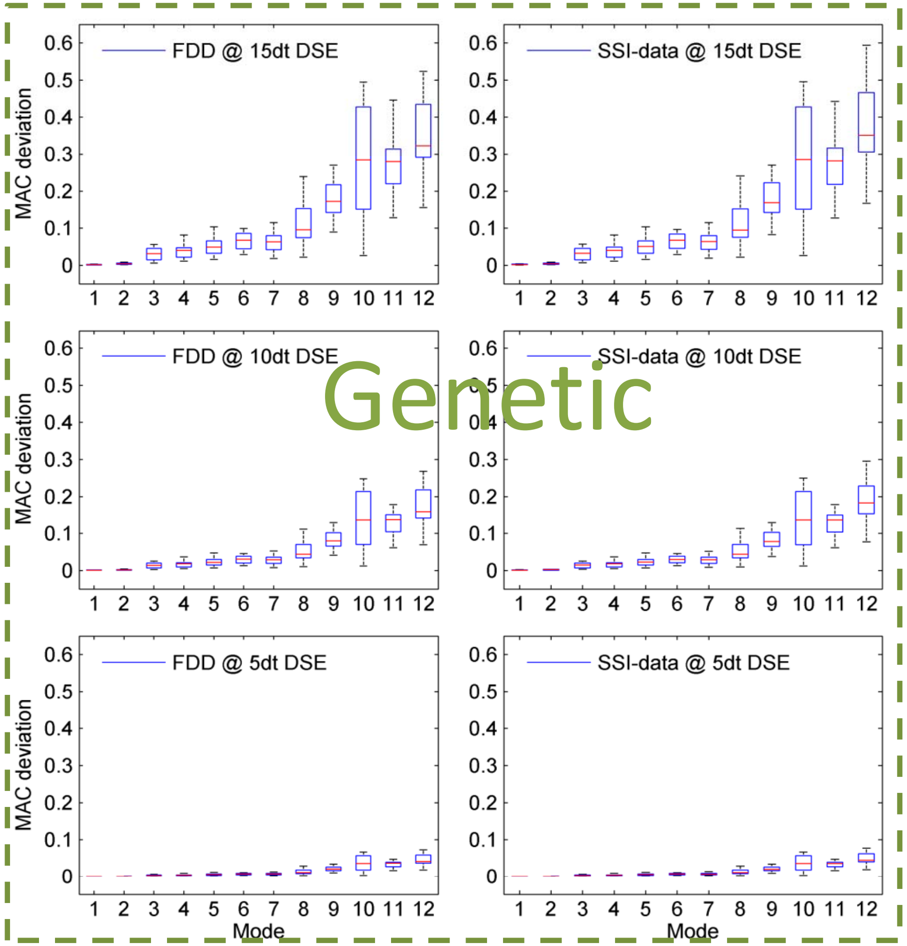
2. Effects of Data Synchronization Error (DSE)

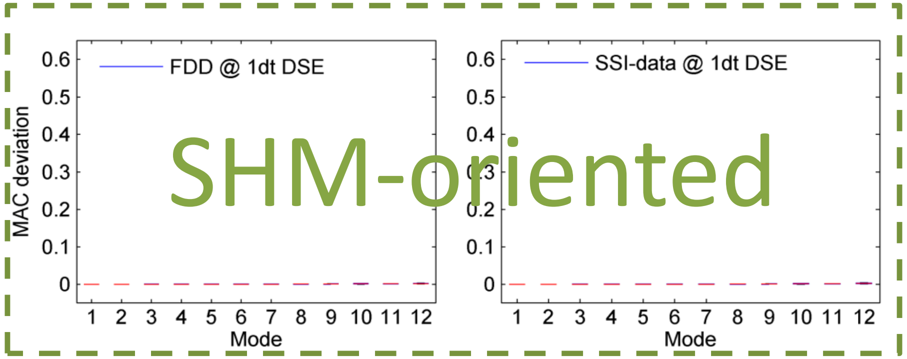


DSE: Data Synchronization Error; FDD: Frequency Domain Decomposition;
SSI-data: data-driven Stochastic Subspace Identification; MAC: Modal Assurance Criterion

Findings for single setup

- **Frequency: No change** for FDD & **almost no change** for SSI-data
- **Mode shape change** (via MAC) : rapidly (non-proportionally) increases for higher DSE levels; higher impact for higher modes
- SSI-data works almost well as FDD





FDD: Frequency Domain Decomposition; SSI-data: data-driven Stochastic Subspace Identification
DSE: Data Synchronization Error; MAC: Modal Assurance Criterion;

SHM research at **QUT** - **Sensors/Measurement**

1. **Vertical Displacement Measurement of bridges using Fibre Bragg Grating (FBG) sensors**

2. **Unsupervised learning novelty detection methods for Vibration Based Damage Detection (VBDD) to cope with Environmental and Operational Variations (EOVs) impacts.**

3. **Develop a practical FBG system for measuring the temperature, strain/displacement and etc. using modulation of FBG strain.**

1. Vertical Displacement Measurement of bridges

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

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

Vertical displacement function, D3

Inclination approach

Slope Measurement 5 FBG tilt sensors

Slope data, s2

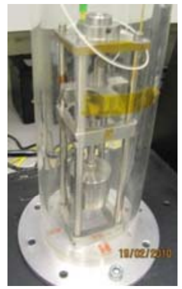
Slope curve, S2

Vertical displacement function, D2

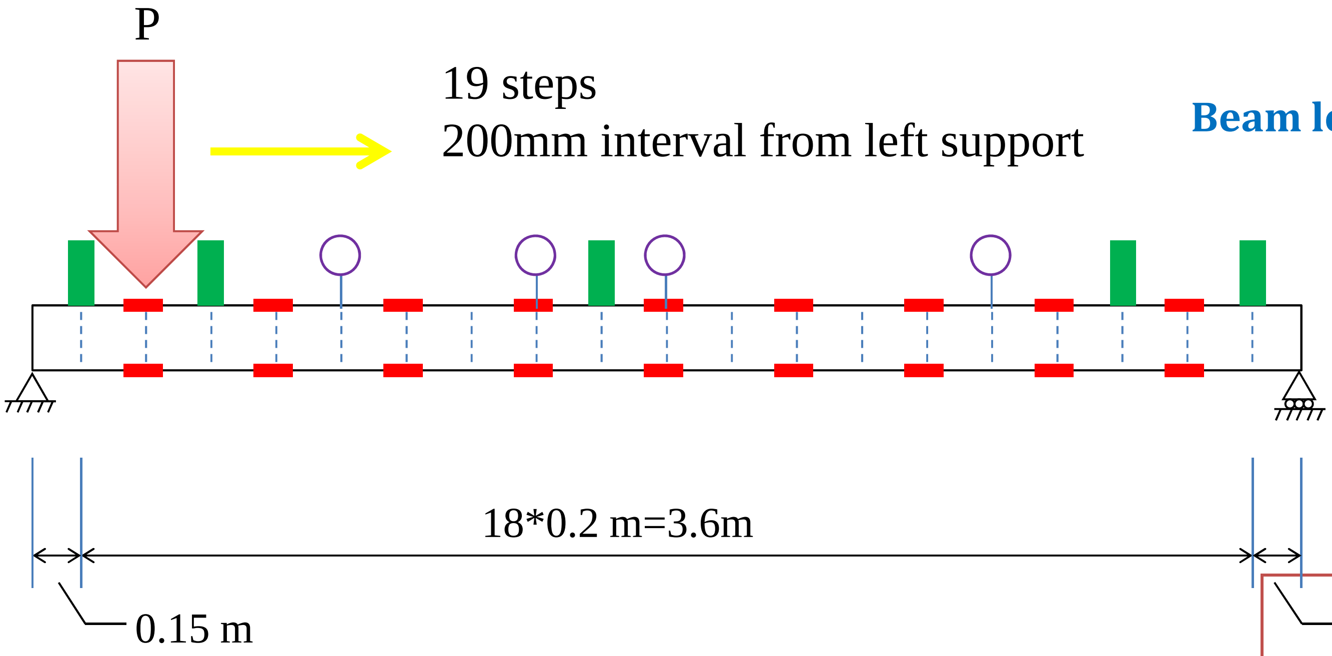
$$\int \theta \, dx$$

Comparing with reference

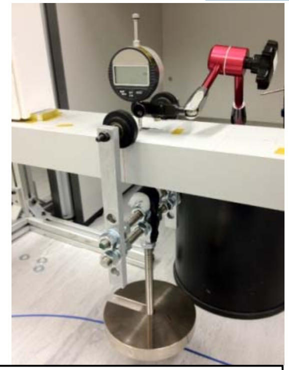
Methodology



Interrogator, sampling of 1kHz



Beam loading test



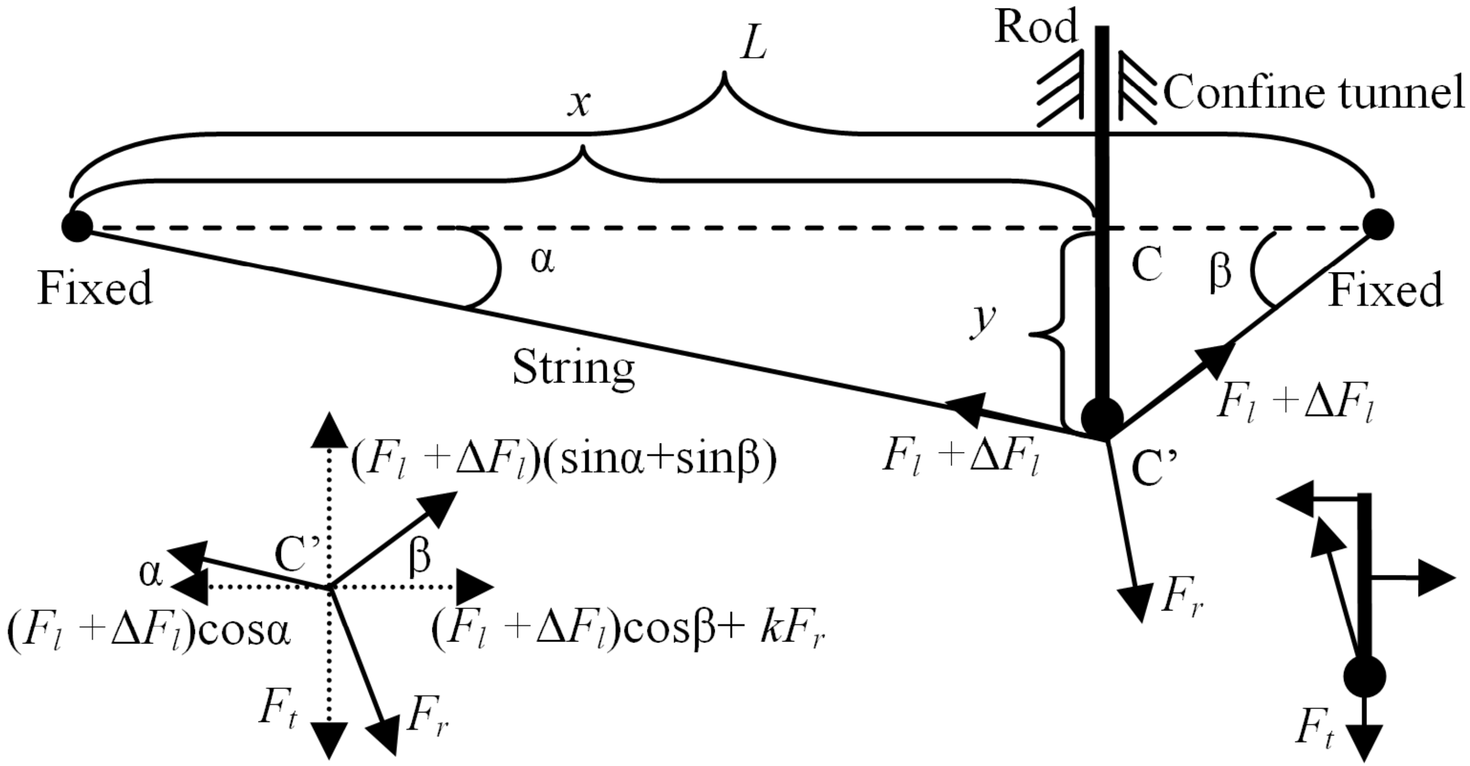
- Sensor configuration
  - 2 arrays FBG sensors (Channel 1 and 2)
  - 5 FBG tilt sensors (Channel 3 and 4)

self-developed FBG tilt sensor

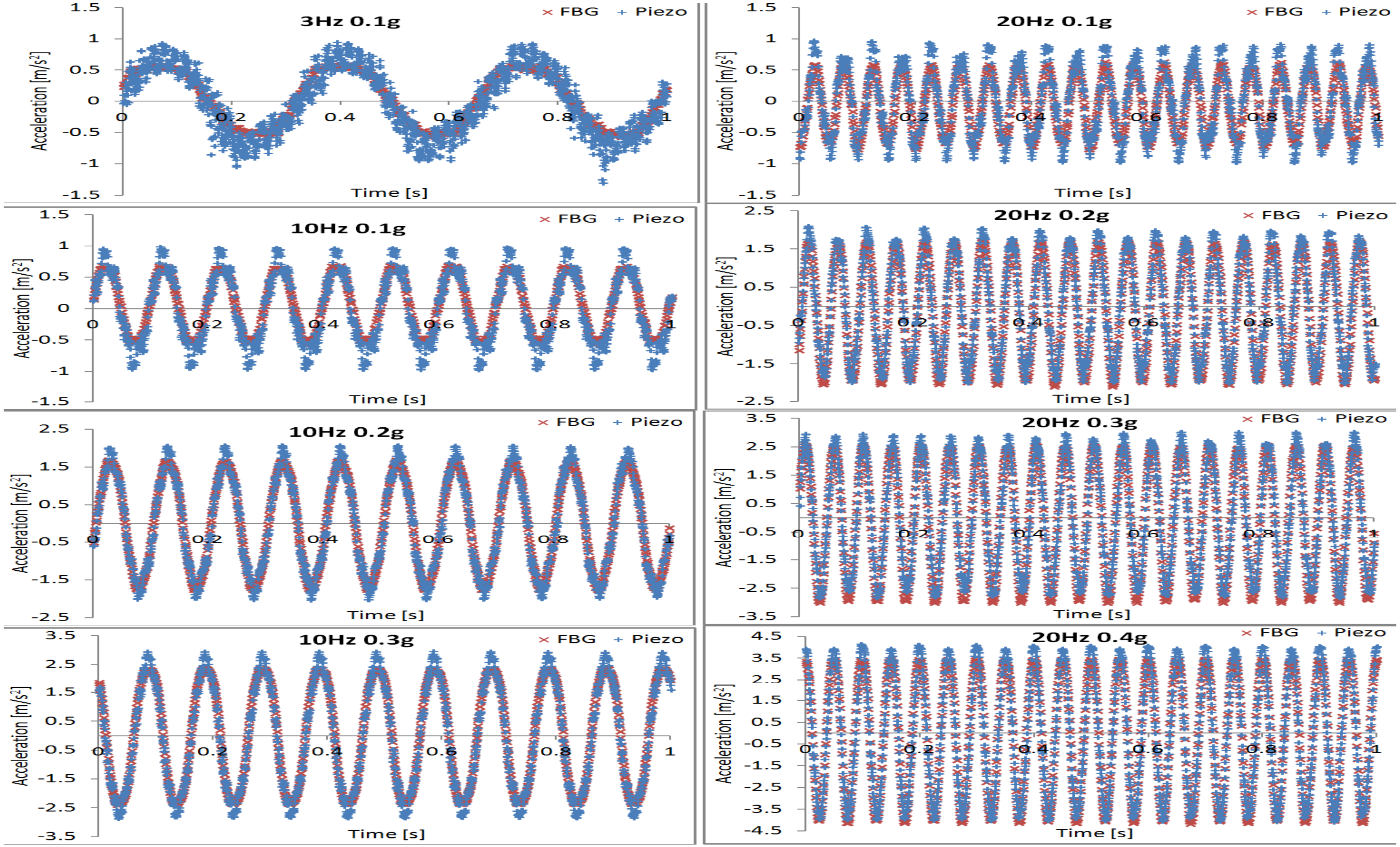
	Accuracy
Curvature approach	>95 %
Inclination approach	>89%

3. Develop a practical FBG system

Theory of the nonlinear string transverse force amplifier



Comparison of FBG and piezo accelerometers results



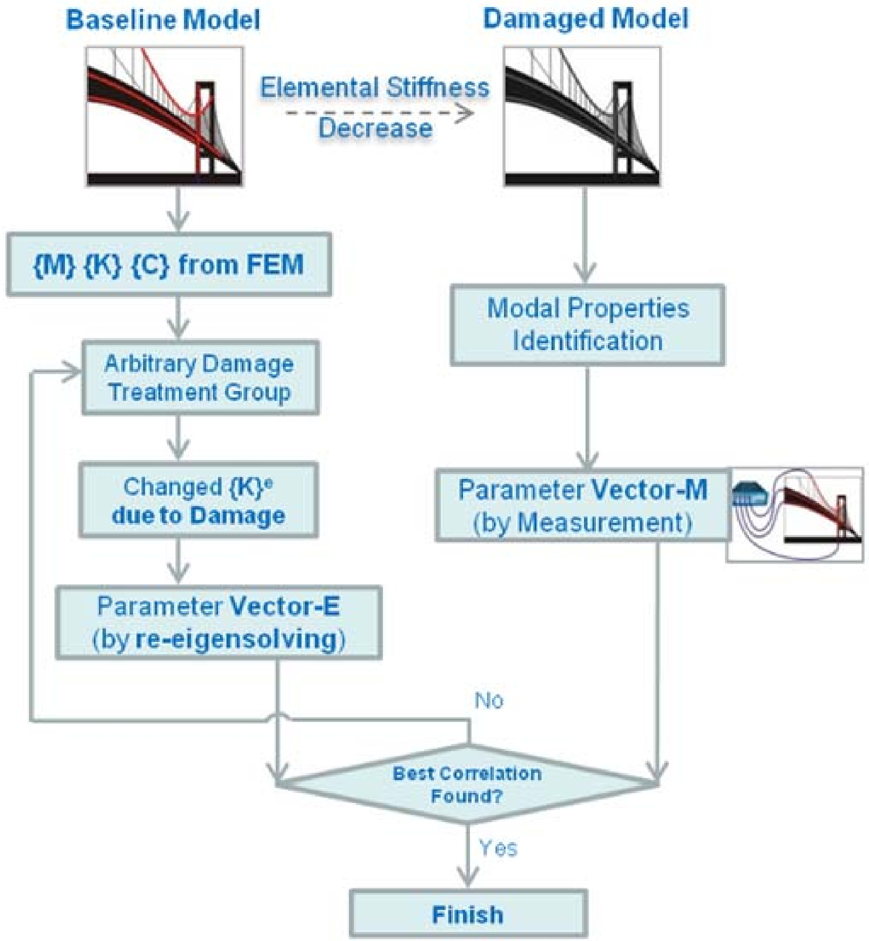
Completed:

1. **Correlation-based Modal Strain Energy (MSEC) employing multi-layer Genetic Algorithms for truss bridges.**
2. **Improved Modal Strain Energy based Damage Index (MSEDI) for Reinforced Concrete Structures.**
3. **A Three-Stage Damage Identification Method for Building Structures Using Frequency Response Functions (FRFs) and Neural Networks (NNs).**
4. **Extract the modal parameters of a heavy-haul-railway RC bridges network.**

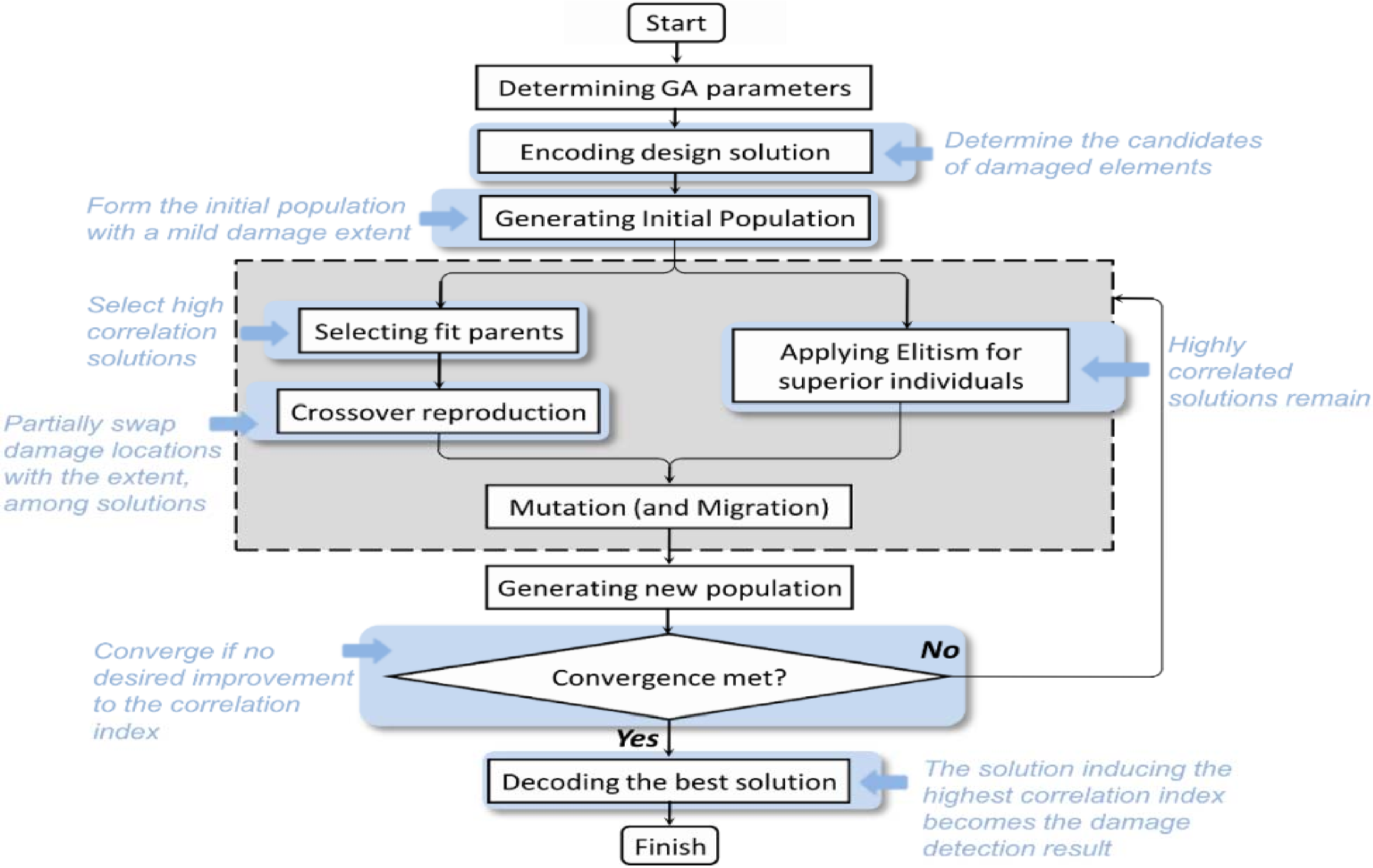
Ongoing:

1. **Synthetic Rating System for Railway Bridge Management.**
2. **An improved Modal Strain Energy method for bridge damage identification.**
3. **Damage detection of suspension bridges using a multi-criteria approach.**

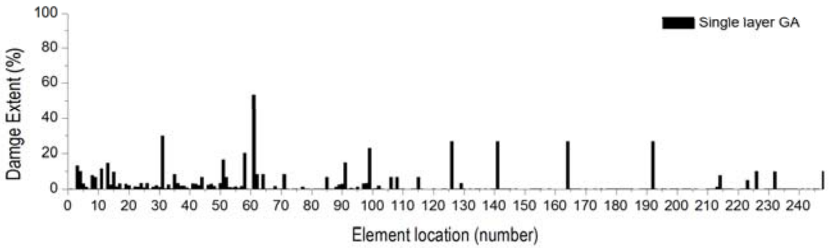
A1. Direct Modal Strain Energy Correlation-based (DMSEC) Method



Advanced Optimisation Technique: Genetic Algorithm (GA)

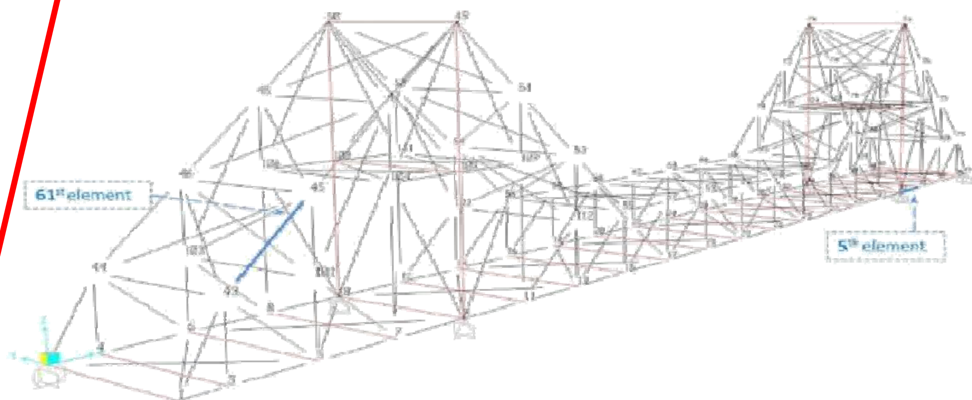


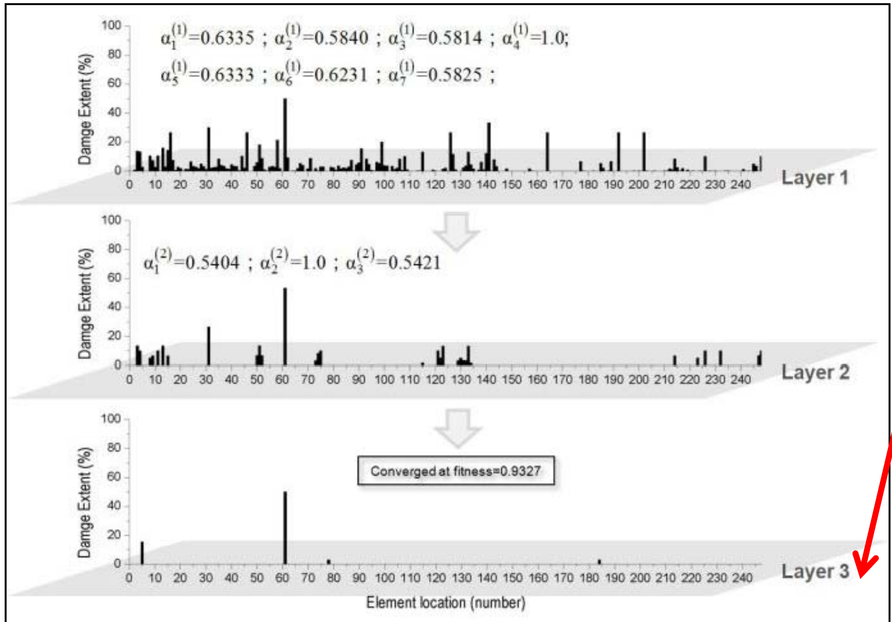
SHM research at **QUT** - Applications



Result of traditional GA-based method

Damage detection improvement





Result of ML-GA method

Damage has been successfully detected at element 5 & 61 at the final layer

A2. Improved Modal Strain Energy based Damage Index (MSEDI)

Theory – DI Formulae, Improved MSEDI

Modification Function

Reduce intensity of false alarms

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

Modal Sensitivity Value (MSV)

During combination of modes

Assign different weight for individual modes

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

Sets the Datum Level to Zero

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

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

$$\beta 2_{(i)}(j,i)=\frac{1+\left(FSE_{ji}\right)_d}{1+\left(FSE_{ji}\right)_u}$$

$$U(j,i)=\frac{EI}{2}\int_{x_j}^{x_{j+1}}\{\varphi_i''\}^2\,dx$$

$$U_i=\frac{EI}{2}\int_0^L\{\varphi''(j,i)\}^2\,dx$$

$$FSE_{ji}=\frac{U_{ji}}{U_i}$$

A3. Three-Stage Damage Identification Method Using FRFs and NNs

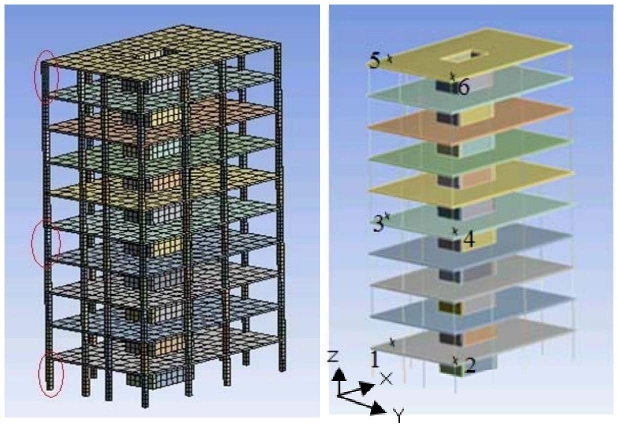
Three-Stage Neural Network Method

Identification of damage floor → Identification of damage element → Severity estimation

Illustrative example

- A low rise building with 10 floors
- Numerical simulations – ANSYS general-purpose FEM analysis software
- Damages simulated by reducing stiffness of elements by a specified ratio (10%, 25%, 40% and 55%)
- 60 damage cases (3 floors x 5 columns x 4 severities)
- 12 measurement locations are available
- Three noise levels-

  1%, 3%, 5% and 10%



Identification of Damaged Floor- first stage

Training, validation and test data partition for the identification of damaged floor

		Damage Location (damaged floor)		
		1st floor	5th floor	10th floor
Damage	10	Train	Train	Test
	25	Val	Test	Train
	40	Test	Train	Val
	55	Train	Val	Train

Training, validation and test partitioning of all FRFs data for identification of damaged floor

Data Set	Samples	Remarks
Training	120	30 damage cases x 4 noise levels
Validation	60	15 damage cases x 4 noise levels
Test	60	15 damage cases x 4 noise levels

A4. Extract the modal parameters of a heavy-haul-railway RC bridges network




Modal Identification Methodology

Three types of recorded signals:

- The short duration free vibration immediately after the train passage (FV);
- The long duration natural ambient vibration between train passages (AV);
- Signals obtained using a drop- weight system (DW) or people jumping over the bridge (PJ)

Two methods were used which are implemented in a commercial software package Artemis® used in this work:

- Enhanced frequency domain decomposition technique (EFDD)
- Stochastic subspace identification technique (SSI)

Identified frequencies for Bridges 5, 15, 20 and 58A

		Free Vibration				Drop Weight				Ambient Vibration						
		SSI		EFDD		SSI		EFDD		SSI		EFDD				FEM
Bridge	N	Freq. (Hz)	Damp.	Freq. (Hz)	Damp.	Freq. (Hz)	Damp.	Freq. (Hz)	Damp.	Freq. (Hz)	Damp.	Freq. (Hz)	Damp.	Mode Type	Mac	Freq. (Hz)
5	1	8.91	1.36%	9.17	0.24%	9.04	1.16%	9.01	0.96%	9.23	1.57%	9.28	1.34%	vertical bending	0.85<M>0.99	9.24
	2					10.77	2.29%	xx	xx					vertical bending	xx	10.19
	3	11.15	0.17%	11.13	0.50%	12.66	0.59%	xx	xx	11.96	0.45%	12.04	0.78%	vert. and lat. bending	0.78<M>0.99	11.55
	4	13.06	0.57%	xx	xx	13.92	0.40%	13.12	1.02%	xx	xx	13.34	0.86%	torsion	0.86<M>0.95	xx
15	1									2.46	3.70%	2.45	1.09%	lateral bending	0.94	2.39
	2	7.46	1.96%	xx	xx					7.47	0.52%	7.46	0.65%	vertical bending	0.95 and 0.96	7.88
	3	8.53	2.15%	xx	xx									lateral bending	xx	8.77
	4									10.40	1.18%	xx	xx	vertical bending	xx	8.96
	5	11.20	0.85%	xx	xx					11.15	1.49%	11.23	1.72%	vertical bending	0.86<M>0.97	11.58
20	1	7.31	1.17%	7.24	1.11%	7.33	1.87%	7.28	0.50%					vertical bending	0.63<M>0.98	6.07
	2					8.16	1.03%	8.13	0.54%					vertical bending	0.8	6.6
	3	8.97	2.97%	9.08	0.59%	9.09	1.35%	xx	xx					torsion	0.55<M>0.78	7.09
58A	1	12.89	2.88%	13.13	1.12%	13.06	2.85%	13.13	2.33%	13.06	3.06%	13.11	3.20%	vertical bending	0.87<M>0.99	14.68
	2	23.22	2.05%	xx	xx	21.50	2.95%	21.84	4.29%	20.52	1.83%	20.71	0.87%	torsion	0.64<M>0.99	xx

B1. Synthetic Rating System for Railway Bridge Management

Factors Criticality

Critical factors categories:

1. Factors which the probability and severance of their occurrence are important:

    - Flood (Fl)
    - Earthquake (Eq)
    - Wind (W)
    - Collision (Col)

2. Factors which gradually degrade the bridge:

    - Environmental and fatigue effects (Ev)

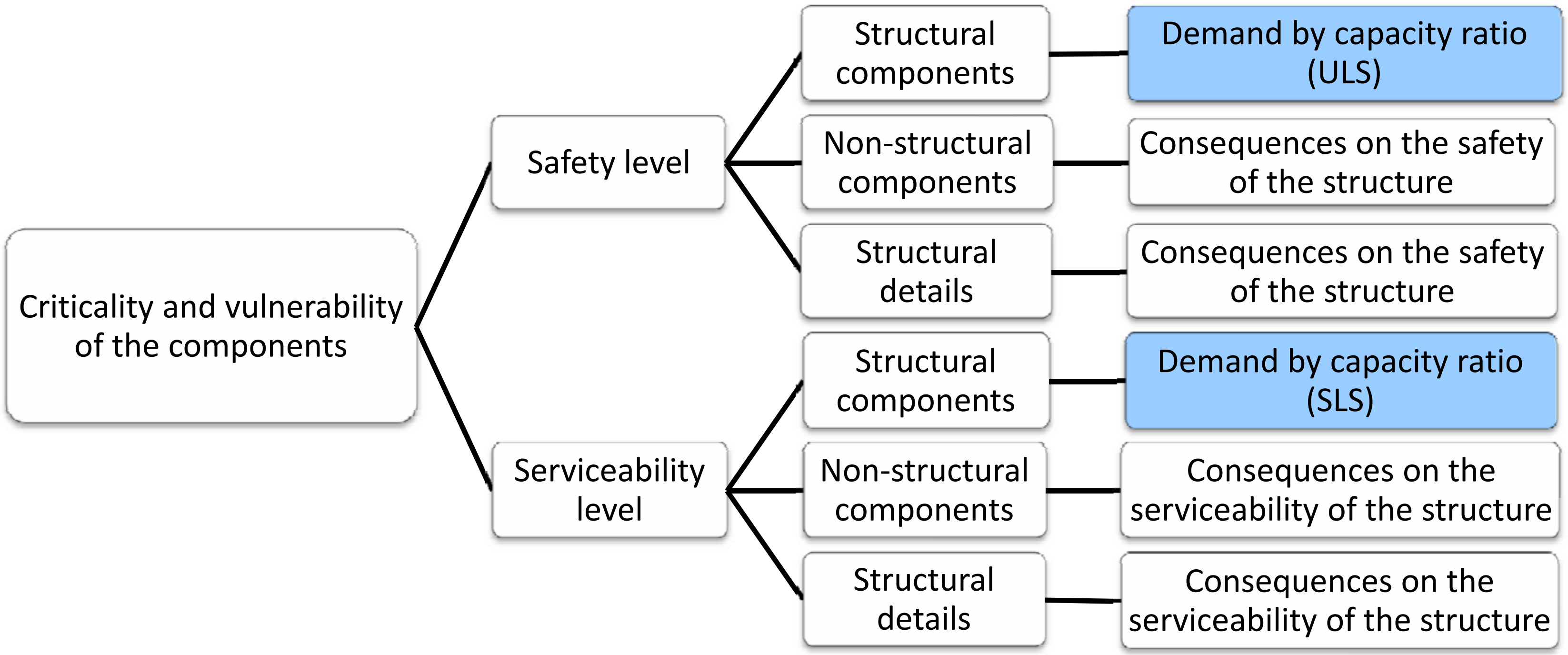
Overall criticality of factors:

Risk analysis conducted in design standards and Analytic Hierarchy Process (AHP) are used to identify the ***Overall criticality of factors***.

$$A = \begin{array}{c} \\ Ev \\ Col \\ Fl \\ W \\ Eq \end{array} \begin{array}{c} \begin{array}{ccccc} Ev & Col & Fl & W & Eq \end{array} \\ \begin{bmatrix} 1 & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & 1 & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & 1 & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & 1 & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & 1 \end{bmatrix} \end{array}$$

Pair-wise comparison matrix used in AHP method

Criticality and vulnerability of the components.



Synthetic Rating Method of Railway Bridge is based on

- Criticality of factors
- Criticality and vulnerability of the components

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B2. An improved Modal Strain Energy Method

1. Improved MSE equation

$$\Delta MSE_{i,j} = \frac{1}{2}\alpha_j\{\phi_i\}^T[K_j]\{\phi_i\} + \frac{1}{2}\left[\{\phi_i\}^T[K_j]\sum_{l=1}^{L}\alpha_l\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_l]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\} + \sum_{l=1}^{L}\alpha_l\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_l]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\}^T[K_j]\{\phi_i\}\right]$$

2.1 Improved Sensitivity Matrix (Equation)

$$\{\phi_i\}^T[K_j]\{\phi_i\} - \{\phi_i^d\}^T[K_j]\{\phi_i^d\} + \sum_{r=1}^{n}\{\phi_i\}^T[K_s]\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\} + \sum_{r=1}^{n}\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\}^T[K_s]\{\phi_i\}$$

2.2 Improved Sensitivity Matrix (Matrix notation)

$$\begin{bmatrix}\beta^*_{11} & 0 & \cdots & 0\\ 0 & \beta^*_{22} & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & \beta^*_{qq}\end{bmatrix} + \begin{bmatrix}\beta'_{11} & \beta'_{12} & \cdots & \beta'_{1q}\\ \beta'_{21} & \beta'_{22} & \cdots & \beta'_{2q}\\ \vdots & \vdots & \ddots & \vdots\\ \beta'_{q1} & \beta'_{q2} & \cdots & \beta'_{qq}\end{bmatrix}$$

3. Fractional reduction coefficients

$$\begin{bmatrix}\alpha_1\\ \alpha_2\\ \vdots\\ \alpha_q\end{bmatrix} = \left(\begin{bmatrix}\beta^*_{11} & 0 & \cdots & 0\\ 0 & \beta^*_{22} & \cdots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \cdots & \beta^*_{qq}\end{bmatrix} + \begin{bmatrix}\beta'_{11} & \beta'_{12} & \cdots & \beta'_{1q}\\ \beta'_{21} & \beta'_{22} & \cdots & \beta'_{2q}\\ \vdots & \vdots & \ddots & \vdots\\ \beta'_{q1} & \beta'_{q2} & \cdots & \beta'_{qq}\end{bmatrix}\right)^{-1}\begin{bmatrix}MSEC_{i1}\\ MSEC_{i2}\\ \vdots\\ MSEC_{iJ}\end{bmatrix}$$

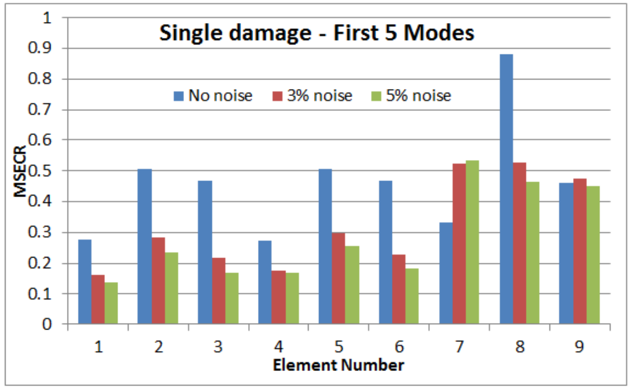
2D verification and simulation

Single-damage scenario

↓

Locating

↓



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Quantifying

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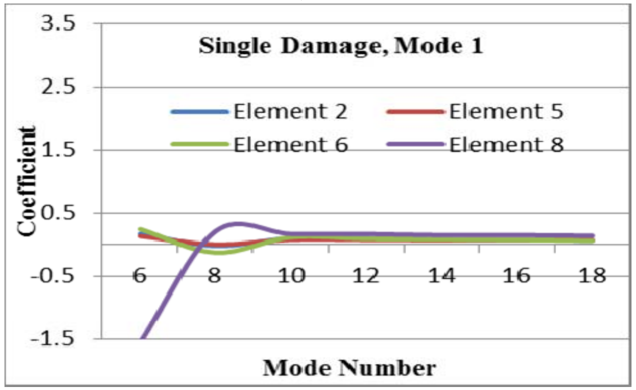
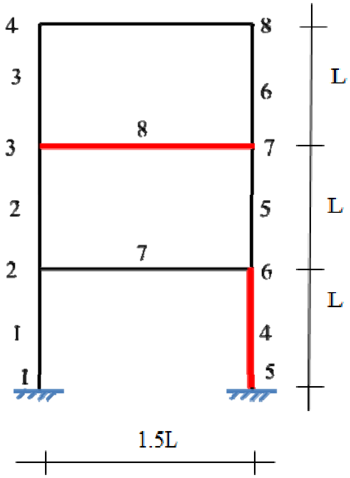


Three-story-Frame structure

8 nodes and 9 elements with 18 DOFs



Material properties and Geometric data:

L= 3.0 m

E=207 × 10⁹ N/m²

A= 0.0015 m²

I=1.125 × 10⁻⁷ m⁴

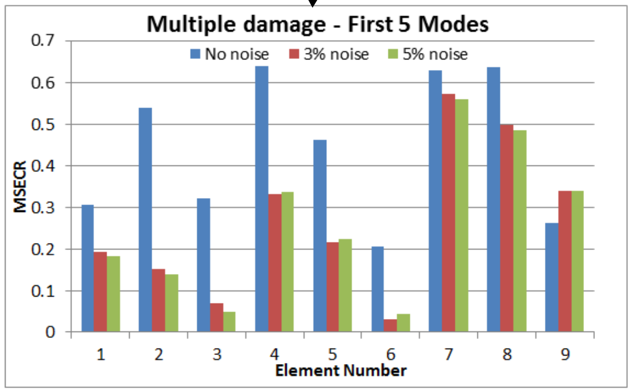
Mass density = 7870 kg/m³

Multiple-damage scenario

↓

Locating

↓



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Quantifying

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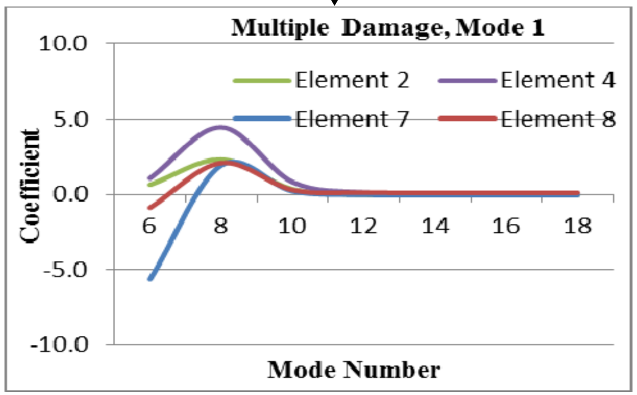
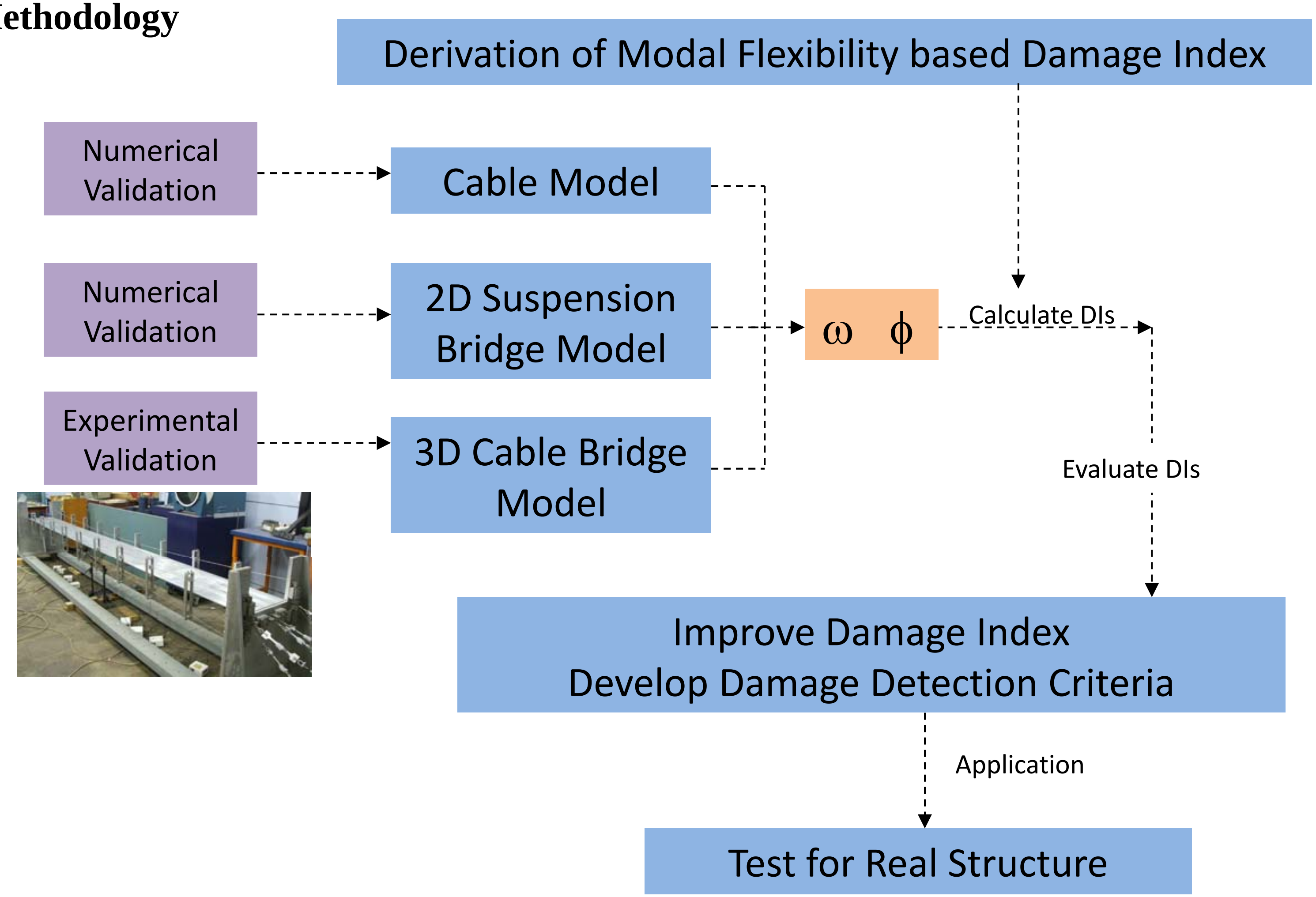
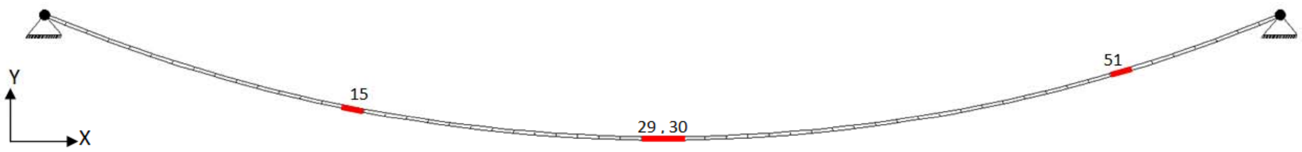


B3. Damage detection of suspension bridges

Methodology



Cable Model

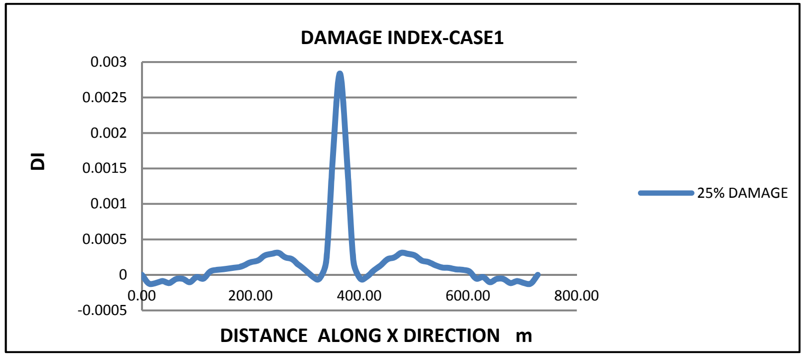


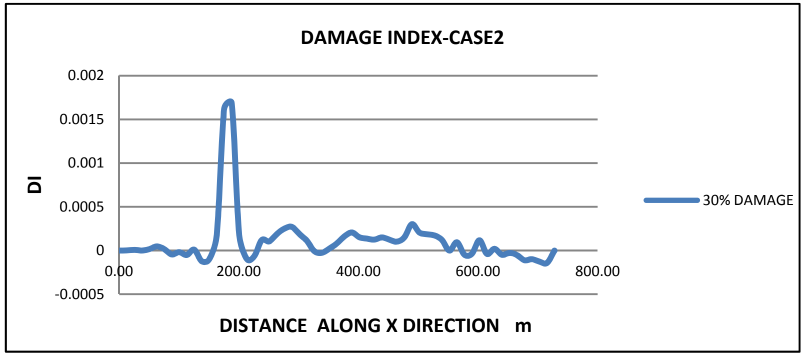
Damage Case1:Element 29,30 — 25% stiffness reduction

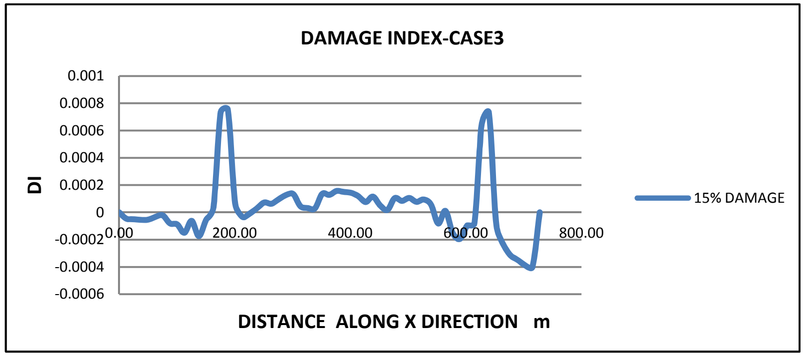
Damage Case2:Element 15 — 30% stiffness reduction

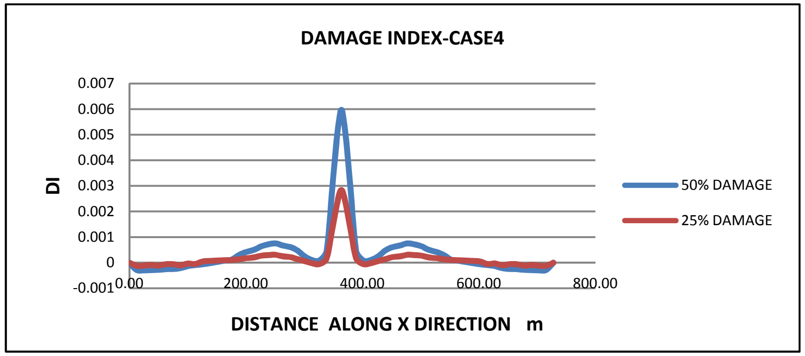
Damage Case3:Element 15,51 — 30% stiffness reduction

Damage Case4:Element 29,30 — 25% and 50% stiffness reduction









Question?