NCREE

結構健康監測新技術

應用巨量數據縮減技術於結構健康診斷及線上子空間系統識別法於結構勁度之即時量化評估

NTU

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2017年8月11日

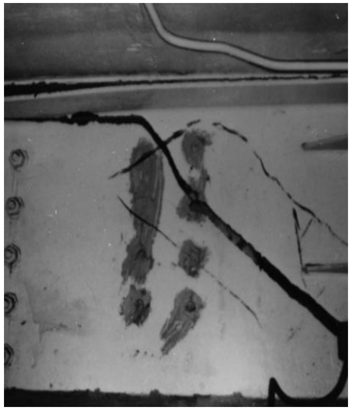
Introduction (I)

Structural damage due to earthquake, scouring, aging, environmental impact load, etc.

Bridge collapse without warning

Bridge during scouring

Building damage during earthquake



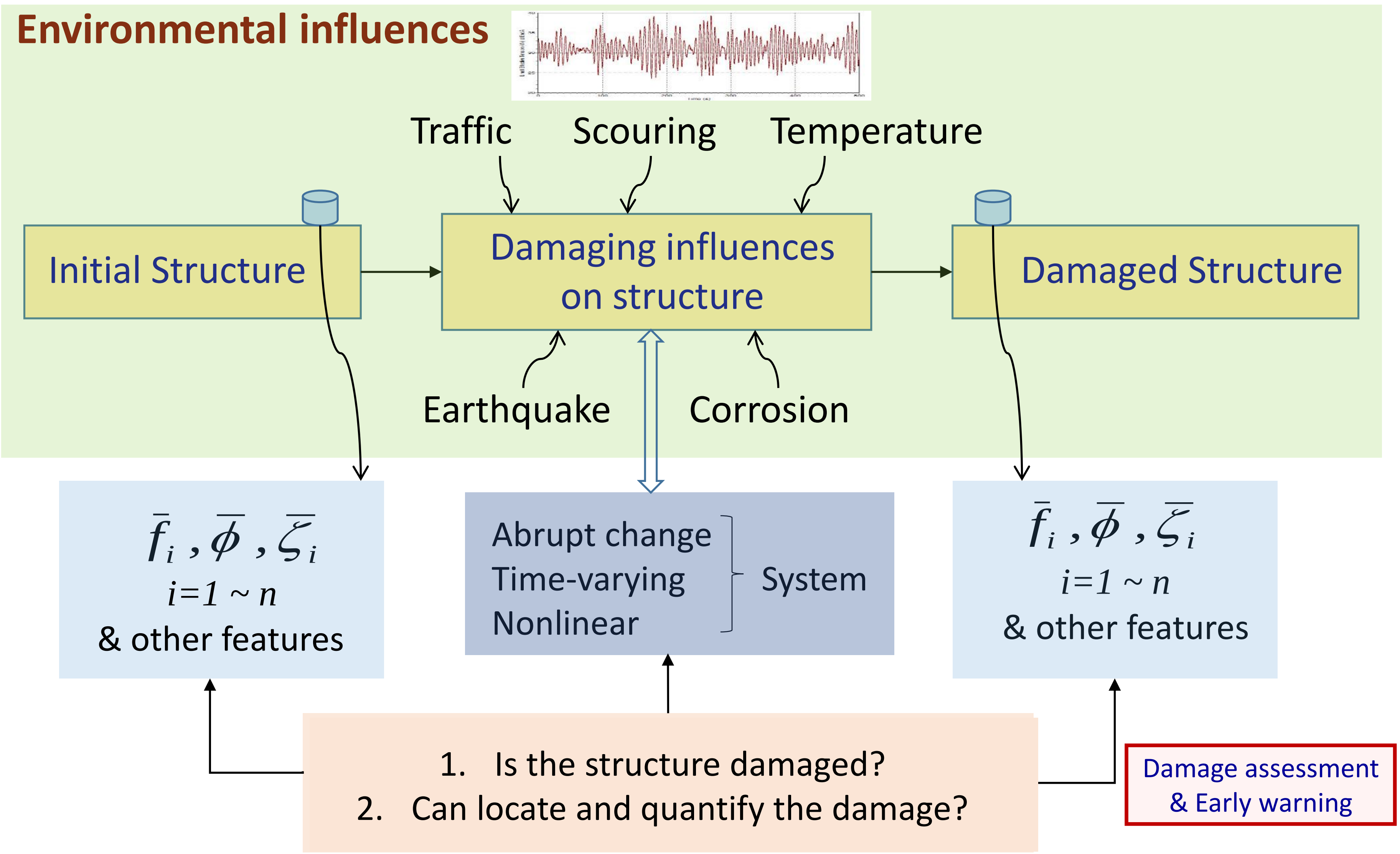
Cracks of steel structure

Wind turbine blade

Collapse of building structure

Collapse Bridge due to scouring

Operation Modal Analysis / Seismic Response for Structural Damage Assessment



Introduction (II)

Damage assessment of structure using **feature extraction** and **system identification** techniques is needed to explore the current state of the structure.

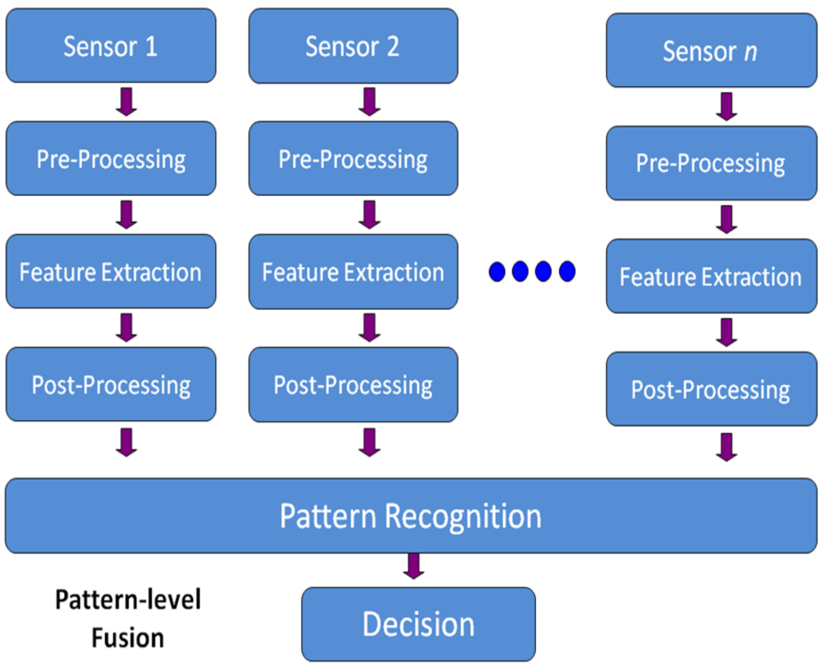
Features are used to answer the following:

1. **Is the system damaged?**
   - Group classification problem for supervised learning
   - Identification of outliers for unsupervised learning
2. **Where is the damage located?**
   - Group classification or regression analysis problem for supervised learning
   - Identification of outliers for unsupervised learning
3. **What type of damage is present?**
   - Can only be answered in a supervised learning mode
   - Group classification
4. **What is the extent of damage?**
   - Can only be answered in a supervised learning mode
   - Group classification or regression analysis
5. **What is the remaining useful life of the structure? (Prognosis)**
   - Can only be answered in a supervised learning mode
   - Regression analysis

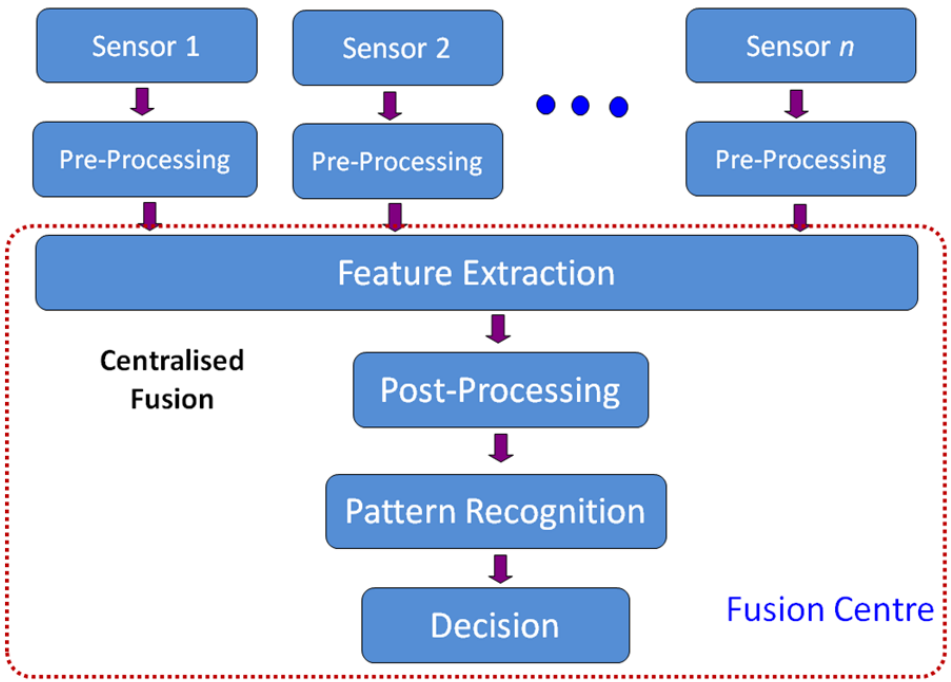
Research Objective

Objective: Develop an **on-line and almost real-time monitoring** of structural modal parameters (or feature extraction techniques) under operating conditions/earthquake loading, and conduct damage assessment on the structure.

Pattern-level Data Fusion



Centralized Data Fusion



Vibration-based damage detection: a ***multi-sensor architecture***

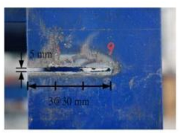
Methodologies for Structural Damage Assessment

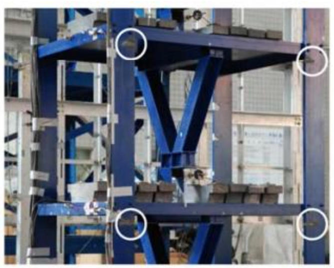
- **結構系統識別方法：**
  - ***結構常態振動量測(微振)***
    - √ 全自動隨機子空間識別法 (Covariance-driven stochastic subspace ID,SSI-COV)
    - √ 多重輸出AR Model (MV-AR)
  - ***結構地震反應量測***
    - √ 子空間識別法 (Subspace Identification, SI)
    - √ 遞迴性子空間系統識別 (Recursive Subspace Identification, RSI)
- **結構健康診斷損傷評估**
  - ***結構常態振動量測(微振)***
    - √ 零子空間損傷識別 (Null-space damage index, Q-test)
    - √ 2D可視化技術結構損傷評估 (Sammon map)
    - √ 相關性指標 (Wavelet-based correlation of scalogram)
    - √ 多重奇異值譜分析法 (Multivariate Singular Spectrum Analysis, MSSA)

    } Level-1 & Level-2
  - ***結構地震反應量測(結合結構系統識別)***
    - √ 勁度折減評估 (LSSM+EMCM)

    } Level-3 & Level-4

Structural Health Monitoring: Experimental Studies

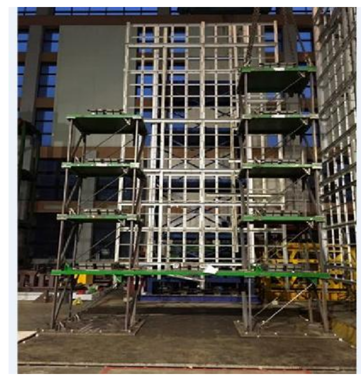




Wind turbine in operating condition

Structural System ID & Damage Assessment

Structure under operating condition



Bridge during scouring process

Building/Bridge under earthquake excitation

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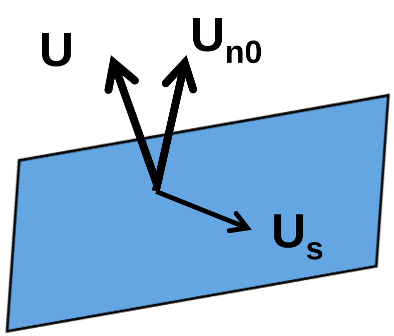
(Level-1 Damage Assessment) Null-space and subspace damage index: DI_n & DI_s

$$\mathbf{Y} = \begin{bmatrix} \mathbf{y}[1] & \mathbf{y}[2] & \cdots & \mathbf{y}[K] \\ \mathbf{y}[2] & \mathbf{y}[3] & \cdots & \mathbf{y}[K+1] \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}[L] & \mathbf{y}[L+1] & \cdots & \mathbf{y}[N] \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_p \\ \hline \mathbf{Y}_f \end{bmatrix} \rightarrow \mathbf{T} = \mathbf{Y}_f \mathbf{Y}_p^T \rightarrow \mathbf{X} = \mathbf{T}$$

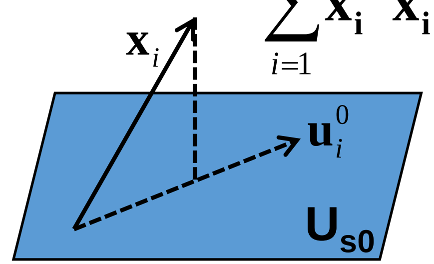
$$\mathbf{X}_0 = [\mathbf{U}_{s0} \quad \mathbf{U}_{n0}] \begin{bmatrix} \mathbf{S}_{s0} & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_{n0} \end{bmatrix} [\mathbf{V}_{s0} \quad \mathbf{V}_{n0}]^T \approx \mathbf{U}_{s0}\mathbf{S}_{s0}\mathbf{V}_{s0}^*$$



$$\mathbf{U}_{n0}^T \mathbf{U}_s \neq \mathbf{0}$$

$$DI_n = mean\{\left|\mathbf{U}_{n0}^T \mathbf{U}_s\right|\}$$

$$\sum_{i=1}^{K} \mathbf{x}_i^T \mathbf{x}_i - \mathbf{x}_i^T \mathbf{U}_{s0} \mathbf{U}_{so}^T \mathbf{x}_i \neq 0$$



$$DI_s = \frac{\sum_{i=1}^{K} \mathbf{x}_i^T \mathbf{x}_i - \mathbf{x}_i^T \mathbf{U}_{s0} \mathbf{U}_{so}^T \mathbf{x}_i}{\sum_{i=1}^{K} \mathbf{x}_i^T \mathbf{x}_i}$$

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Stage I: Decomposition

Step 1: Embedding.

1. Develop the trajectory matrix: (from each record)

$$X_l = \begin{bmatrix} x_l(1) & x_l(2) & \cdots & x_l(M) \\ x_l(2) & x_l(3) & \cdots & x_l(M+1) \\ \vdots & \vdots & \vdots & \vdots \\ x_l(N') & x_l(N'+1) & \cdots & x_l(N) \end{bmatrix}$$

2. Develop block Hankel trajectory matrix: (combine all records)

$$X_V = \begin{bmatrix} X_1 \\ \vdots \\ X_D \end{bmatrix}$$

Step 2: Singular Value Decomposition

3. Perform SVD of X_V.:

$$X_V = X_{V1} + X_{V2} + \cdots + X_{VLsum}$$

where $X_{Vi} = \sqrt{\lambda_i} U_{Vi} V_{Vi}^T$ $\quad V_{Vi} = X_V^T U_{Vi} / \sqrt{\lambda_{Vi}}$

$\lambda_{V_1}, \cdots, \lambda_{V_{Lsum}}$ and $U_{V_1}, \cdots, U_{VLsum}$

are the eigenvalue and eigenvector of $X_V X_V^T$

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Damage Detection Algorithms: Centralized fusion (MSSA)

Stage II: Reconstruction

Block Hankel trajectory matrix $X_V = \begin{bmatrix} X_1 \\ \vdots \\ X_D \end{bmatrix}$

$$\tilde{C} = X_V X_V^{\,T} = \begin{pmatrix} X_1 X_1^T & X_1 X_2^T & \cdots & X_1 X_D^T \\ X_2 X_1^T & X_2 X_2^T & \cdots & X_2 X_D^T \\ \vdots & \vdots & X_d X_{d'}^T & \vdots \\ X_D X_1^T & X_D X_2^T & \cdots & X_D X_D^T \end{pmatrix}$$

Eigenelements: Determine eigenvalues and eigenvectors of $\widetilde{\mathbf{C}}$

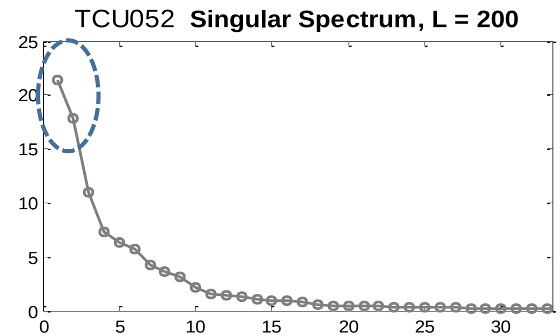
$$\widetilde{\mathbf{C}}\widetilde{\mathbf{e}}_k = \lambda_k \widetilde{\mathbf{e}}_k, \qquad k = 1 \dots D\,M$$

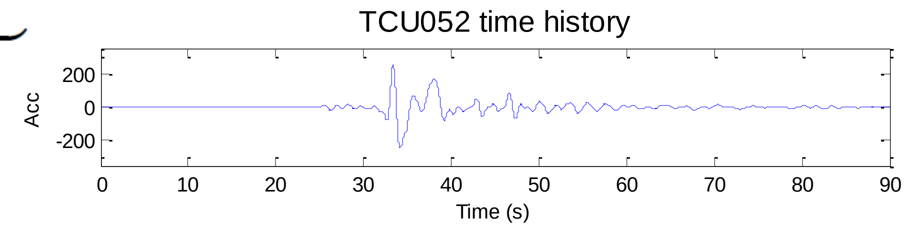
Principal components: Project $X(t)$ onto $\widetilde{\mathbf{e}}_k$

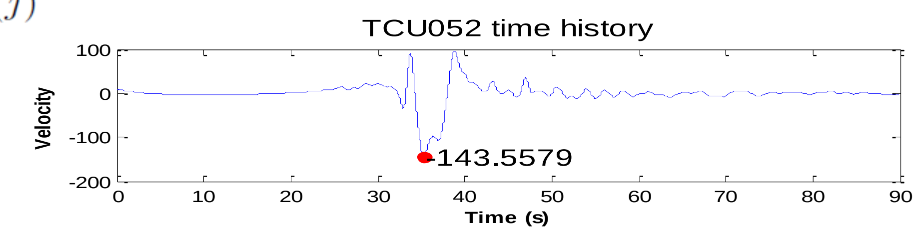
$$A_k(t) = \sum_{d=1}^{D} \underbrace{\sum_{j=1}^{M} x_d(t+j-1)\mathrm{e}_k^d(j)}_{\text{SSA}}$$

Reconstructed components: Combine PCs with $\widetilde{\mathbf{e}}_k$

$$r_k^d(t) = \frac{1}{M}\sum_{j=1}^{M} A_k(t-j+1)\mathrm{e}_k^d(j)$$







System Identification: **SSI-COV** (for ambient data))

Gather the output data in data sequence vector:

$$y_k^+ \equiv \begin{bmatrix} y_{k-i+1} \\ y_{k-i+2} \\ \dots \\ y_k \end{bmatrix}, \; y_k^{-T} \equiv \begin{bmatrix} y_{k-i}^T & y_{k-i-1}^T & \dots & y_{k-2i+1}^T \end{bmatrix}$$

$$y_k^+ \in \Re^{il\times 1} \qquad y_k^{-T} \in \Re^{1\times il}$$

l is the number of sensors and
i is number of block rows

Form the block Hankel covariance matrix:

$$\mathbf{H}_N^{\mathrm{cov}} = E[y_k^+ y_k^{-T}] = \frac{1}{\tilde{p}} \sum_{k=2i}^{N} y_k^+ y_k^{-T}$$

Factorization of the block Hankel covariance matrix through SVD:

$$\mathbf{H}^{\mathrm{cov}} = \begin{bmatrix} \mathbf{R}_1 & \mathbf{R}_2 & \dots & \mathbf{R}_i \\ \mathbf{R}_2 & \mathbf{R}_3 & \dots & \mathbf{R}_{i+1} \\ \dots & \dots & \dots & \dots \\ \mathbf{R}_i & \mathbf{R}_{i+1} & \dots & \mathbf{R}_{2i-1} \end{bmatrix} = \mathbf{O}_i \mathbf{\Omega}_i = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \dots \\ \mathbf{CA}^{i-1} \end{bmatrix} \begin{bmatrix} \mathbf{G} & \mathbf{AG} & \dots & \mathbf{A}^{i-1}\mathbf{G} \end{bmatrix}$$

$$\mathbf{R}_i = E[\mathbf{y}_k \, \mathbf{y}_{k-i}^T]$$

Traditional Singular Value Decomposition:

System order

$$\mathbf{H}^{\mathrm{cov}} = \mathbf{USV}^T = \begin{pmatrix} \mathbf{U}_1 & \mathbf{U}_2 \end{pmatrix} \begin{pmatrix} \mathbf{S}_1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{V}_1^T \\ \mathbf{V}_2^T \end{pmatrix}$$

Find the Observability matrix $\mathbf{O}_i$ from the column subspace $\mathbf{U}_1$:

$$\mathbf{O}_i = \mathbf{U}_1 \mathbf{S}_1^{1/2}$$

Obtain the system matrices (**A**,**C**):

$$\mathbf{C} = \mathbf{O}_i(1{:}l,:)$$

$$\begin{bmatrix} \mathbf{CA} \\ \mathbf{CA}^2 \\ \dots \\ \mathbf{CA}^i \end{bmatrix} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \dots \\ \mathbf{CA}^{i-1} \end{bmatrix} \mathbf{A}$$

$$\mathbf{A} = \mathbf{O}_i(1{:}l(i-1),:)^{\dagger} \mathbf{O}_i(l+1{:}li,:)$$

Subspace Identification: Tradition (for EQ excitation)

$$X_{(k+1)} = A_d \cdot X_{(k)} + B_d \cdot u_{(k)} + w_{(k)}$$
$$y_{(k+1)} = C_c \cdot X_{(k)} + D_c \cdot u_{(k)} + v_{(k)}$$

$\Rightarrow$

$$Y_f = \Gamma_i \cdot X_f + H_i \cdot U_f + G_i \cdot W_f + V_f$$

Approach 1: Orthogonal Projection:

$U_f \rightarrow$
$$Y_{f(k)}\Pi^{\perp}_{U_{f(k)}} = \Gamma_i X_f \cdot \Pi^{\perp}_{U_{f(k)}} + H_i U_{f(k)} \cdot \Pi^{\perp}_{U_{f(k)}} + G_i W_{f(k)} \cdot \Pi^{\perp}_{U_{f(k)}} + V_{f(k)} \cdot \Pi^{\perp}_{U_{f(k)}}$$

$\Xi^T_p \rightarrow$
$$Y_{f(k)}\Pi^{\perp}_{U_{f(k)}}\Xi^T_{p(k)} = \Gamma_i X_f \Pi^{\perp}_{U_{f(k)}} \cdot \Xi^T_{p(k)} + G_i W_{f(k)}\Pi^{\perp}_{U_{f(k)}} \cdot \Xi^T_{p(k)} + V_{f(k)}\Pi^{\perp}_{U_{f(k)}} \cdot \Xi^T_{p(k)}$$
$$\approx \Gamma_i X_f \Pi^{\perp}_{U_{f(k)}} \Xi^T_{p(k)}$$

$$O^{Orthogonal}_{(k)} = Y_{f(k)}\Pi^{\perp}_{U_{f(k)}}\Xi^T_{p(k)}$$
$$= USV^T = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} S_1 & 0 \\ 0 & S_2 \approx 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} \approx U_1 S_1 V_1^T$$
$$\Gamma_i^{Orthogonal} \,\square\, U_1$$

Approach 2: Oblique Projection:

$$O^{Oblique}_{(k)} = (Y_{f(k)} /_{U_{f(k)}} \Xi_{p(k)}) / U^{\perp}_{f(k)} = \Gamma_i \cdot X_f / U^{\perp}_{f(k)}$$
$$= USV^T = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} S_1 & 0 \\ 0 & S_2 \approx 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} \approx U_1 S_1 V_1^T \rightarrow \Gamma_i^{Oblique} \,\square\, U_1$$

Multi-variable Output Error State sPace algorithm

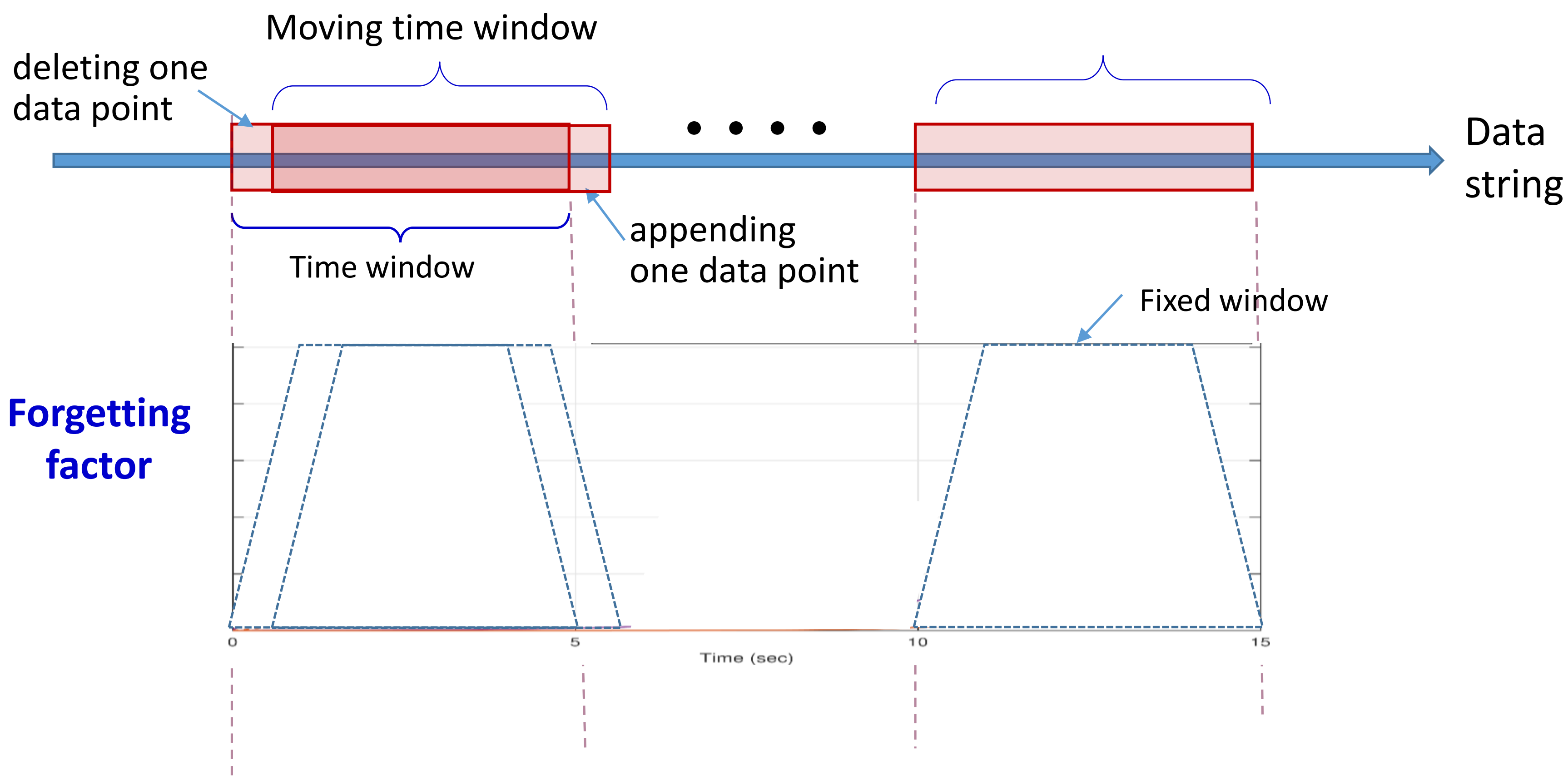
Extended observability matrix
$$\Gamma_i \equiv \begin{bmatrix} C_c \\ C_c A_d \\ C_c A_d^{\,2} \\ \vdots \\ C_c A_d^{\,i-1} \end{bmatrix} \in R^{li \times 2n}$$

$$\begin{bmatrix} U_{f(k)} \\ \Xi_{p(k)} \\ Y_{f(k)} \end{bmatrix}_{2i(m+l)\times j} = \begin{bmatrix} L_{11(k)} & 0 & 0 \\ L_{21(k)} & L_{22(k)} & 0 \\ L_{31(k)} & L_{32(k)} & L_{33(k)} \end{bmatrix}_{2i(m+l)\times 2i(m+l)} \cdot \begin{bmatrix} Q^T_{1(k)} \\ Q^T_{2(k)} \\ Q^T_{3(k)} \end{bmatrix}_{2i(m+l)\times j}$$

$$O^{Oblique}_{(k)} = Y_{f(k)} /_{U_{f(k)}} \Xi_{p(k)} / U^{\perp}_{f(k)} = L_{32(k)} Q^T_{2(k)}$$

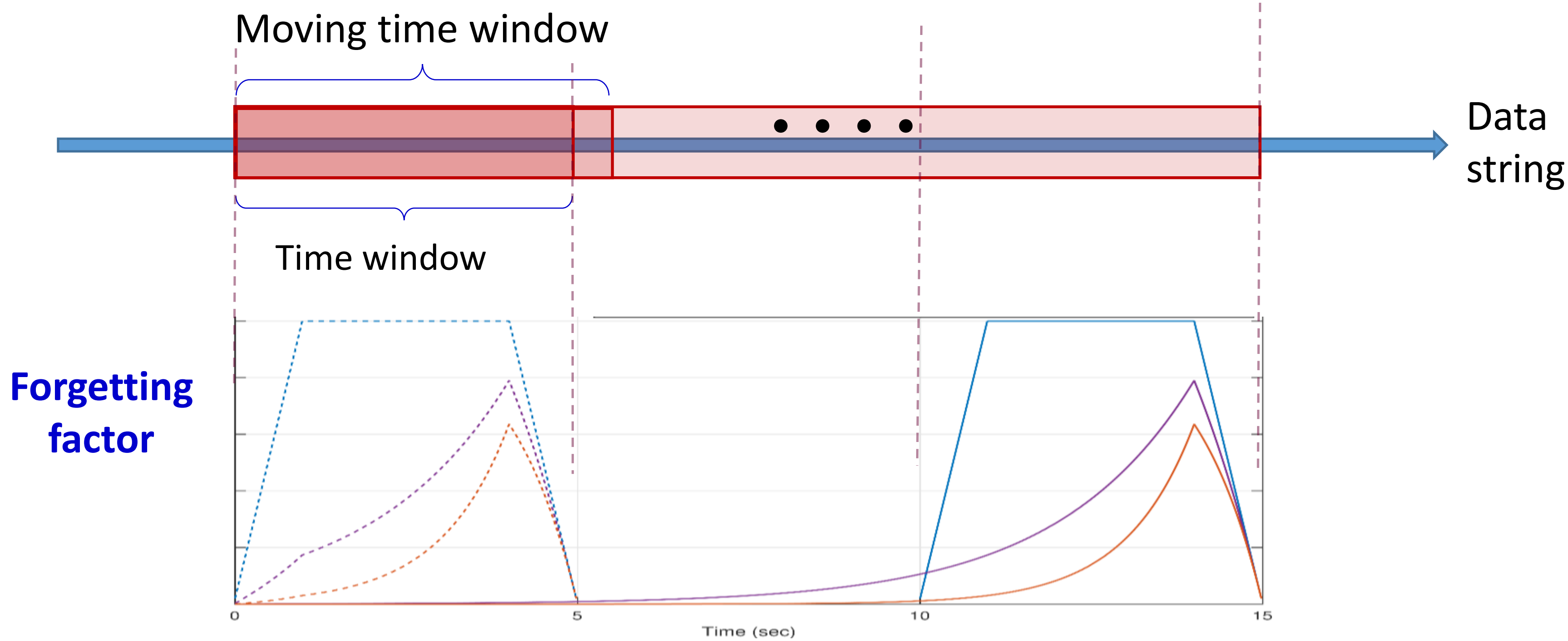
Oblique Projection $\Rightarrow$ **(1) Direct expansion** **(2) LQ - decomposition**

Method 1 (BonaFide RSI): Fixed-length window



Recursive Identification (with/without forgetting factor)

Method 2: Enlarged-length window



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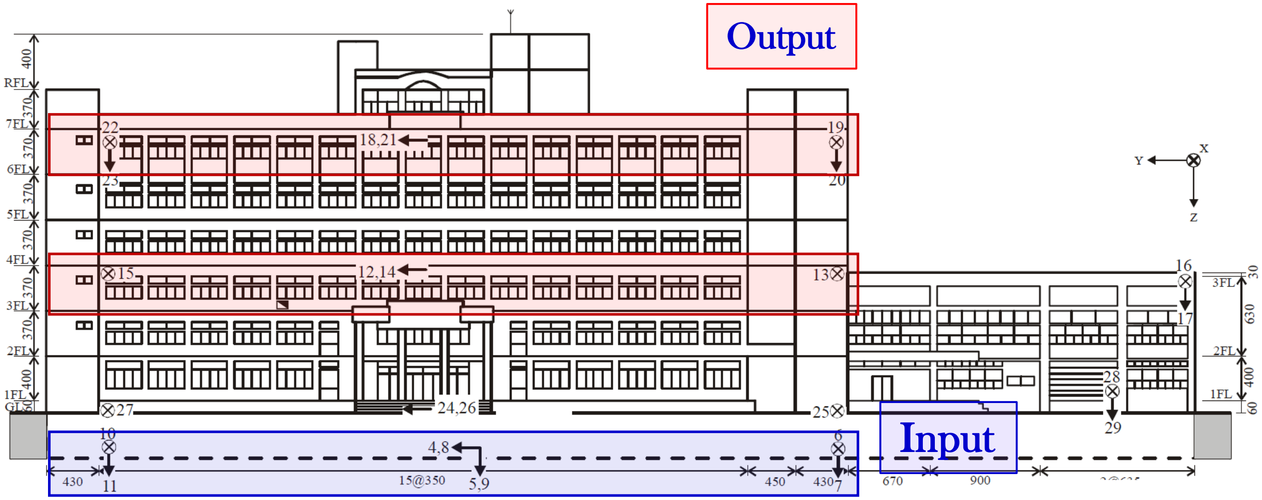
CASE 1 Study: Damage Assessment of Building Structure Using RSI



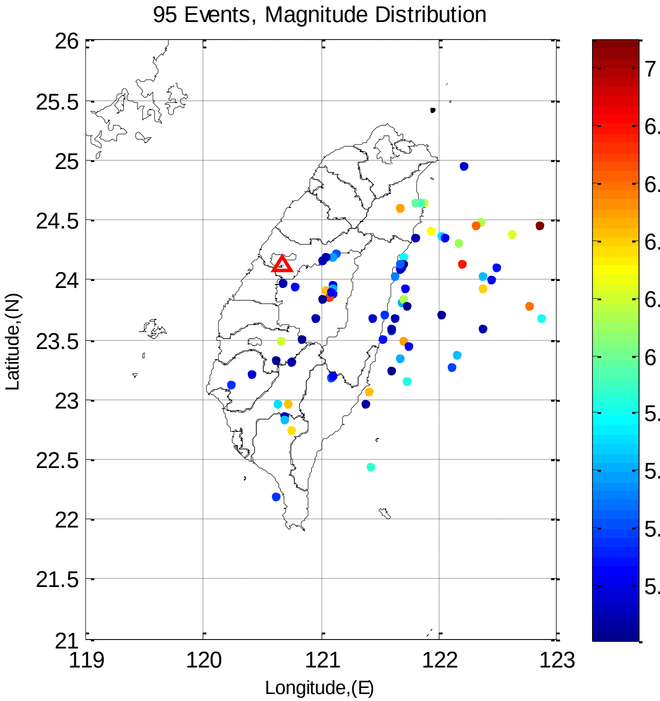
Structural Type：

7-story with one story of basement

RC building with wall and open core

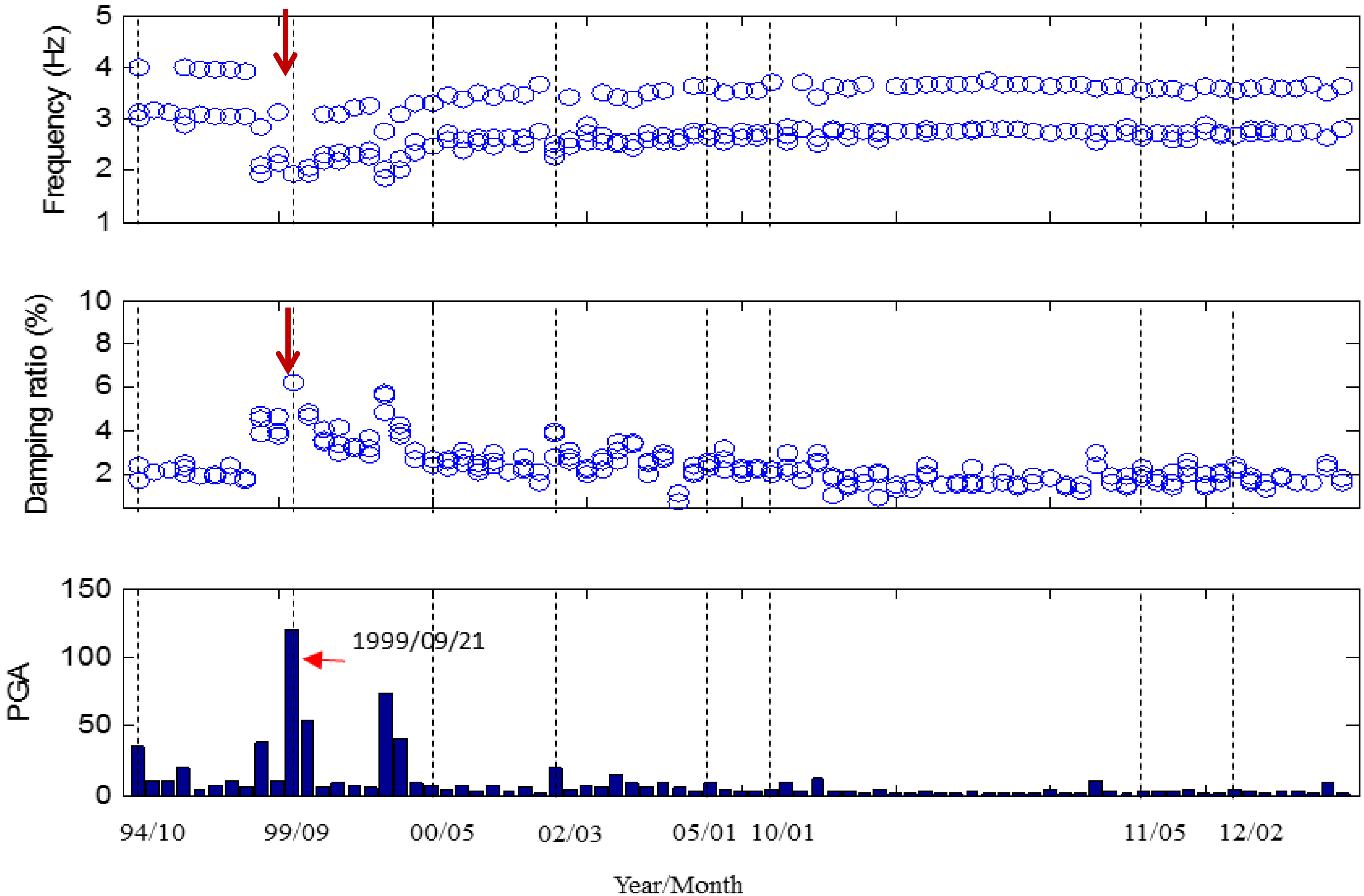
Total number of channels:

29（INCLUDING FREE FIELD）



CE-NCHU Building

1994 ~2013 : 79 events



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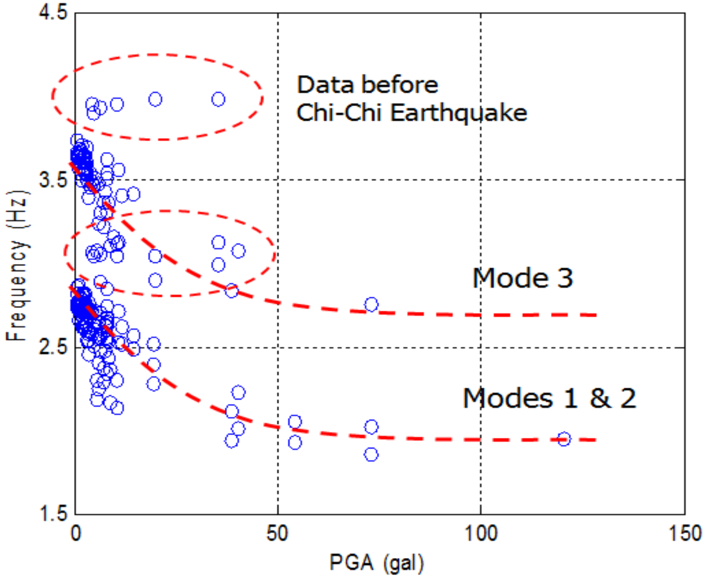
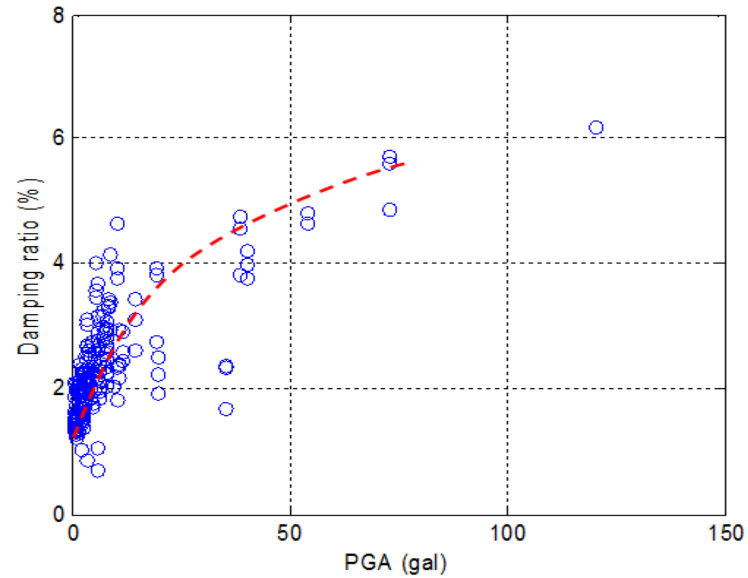
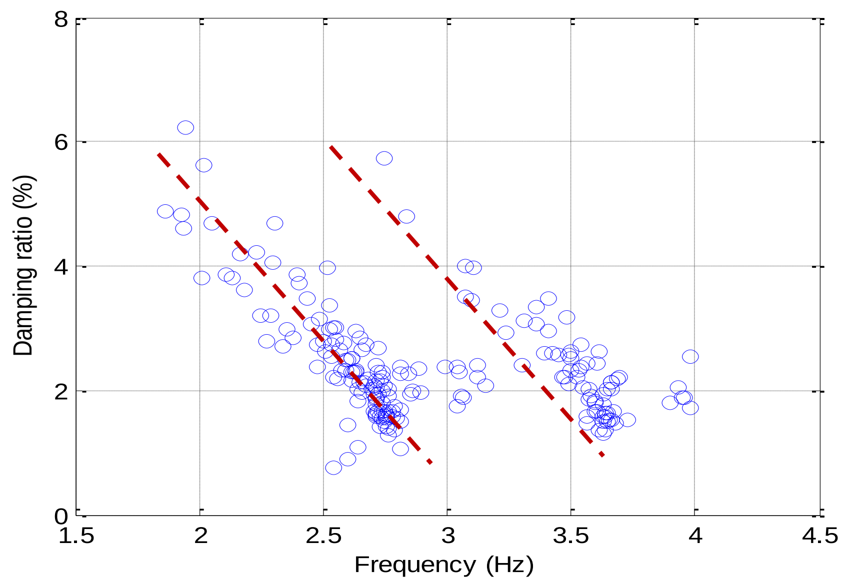
Damage Assessment of Building Structure Using RSI



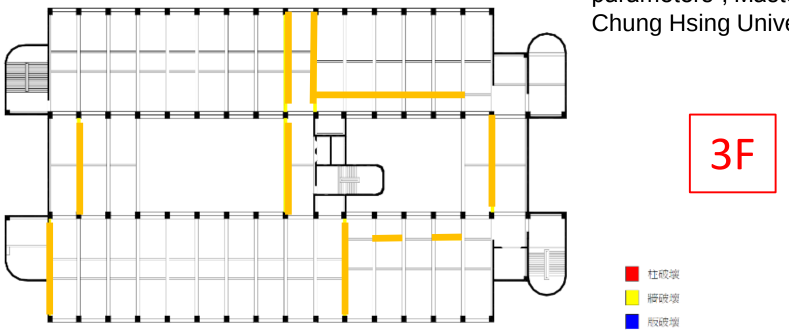


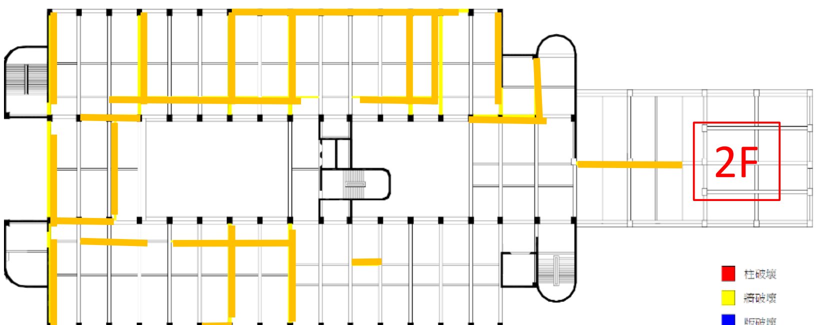


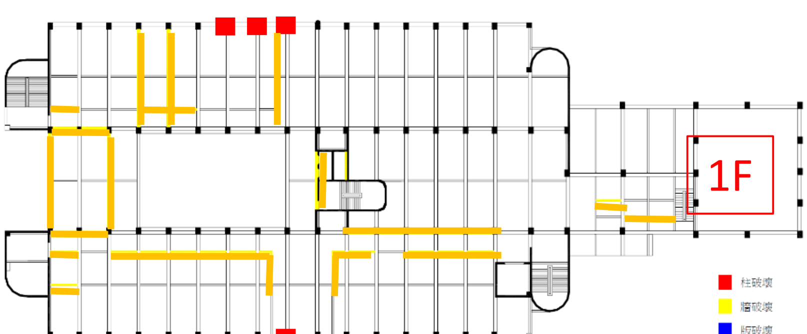
Damage Assessment of Building Structure Using RSI

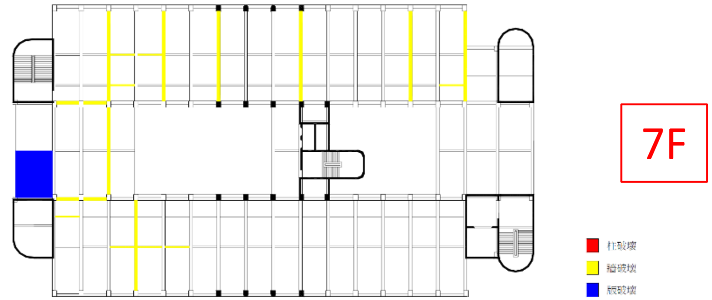
- Damage on column
- Damage on slab
- Damage on wall

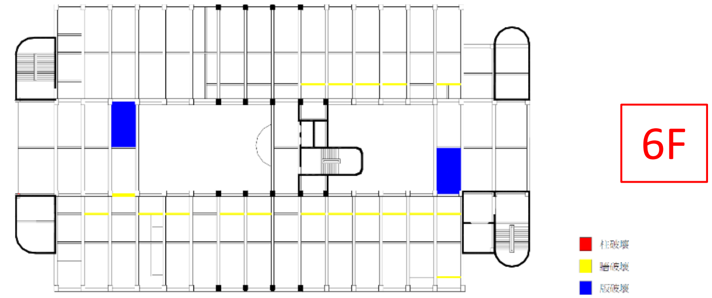
Ref: S.M. Yen, "Story damage index for buildings based on identified modal parameters", Master thesis of National Chung Hsing University (2005).

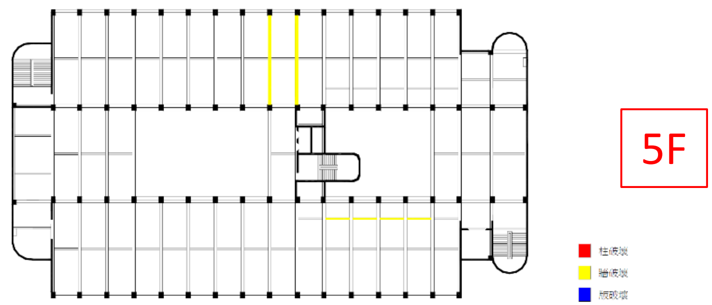


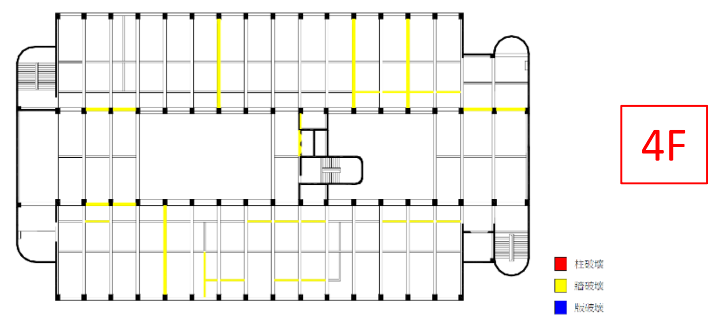




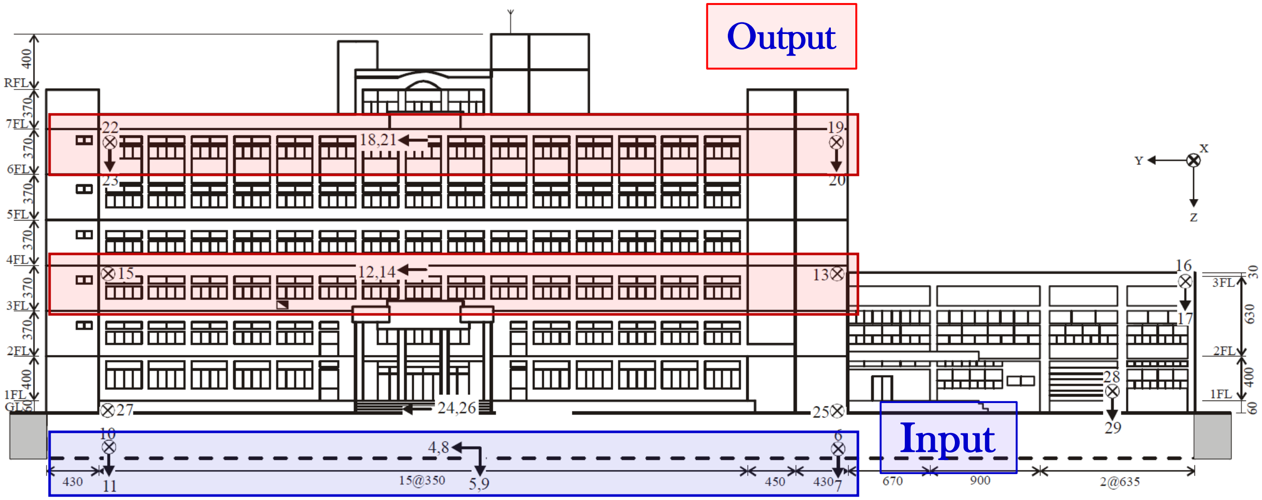


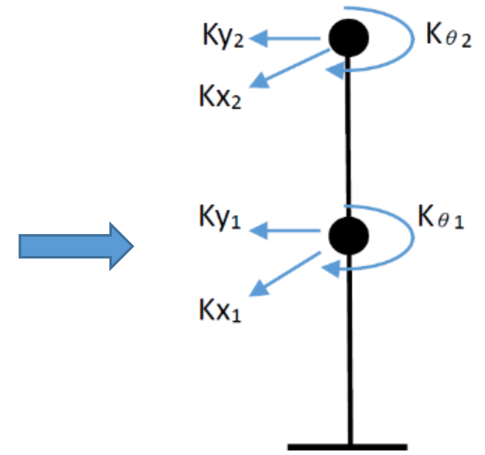




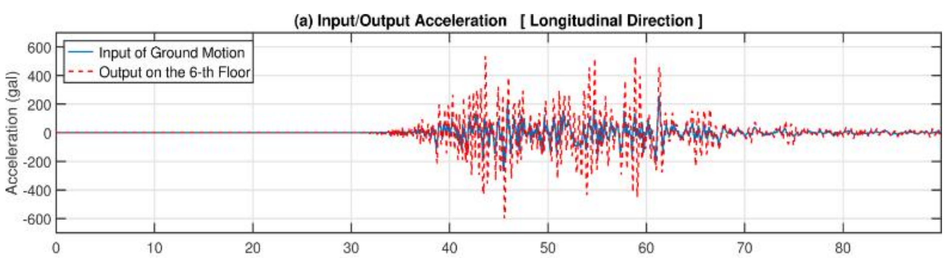


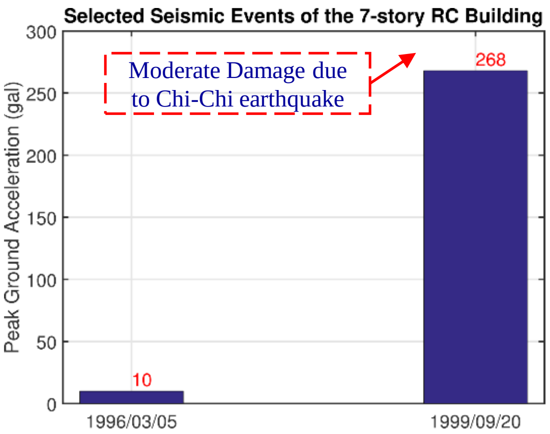
CASE 1 Study: Damage Assessment of Building Structure Using RSI





Simplified 2-story Torsionally Coupled Model





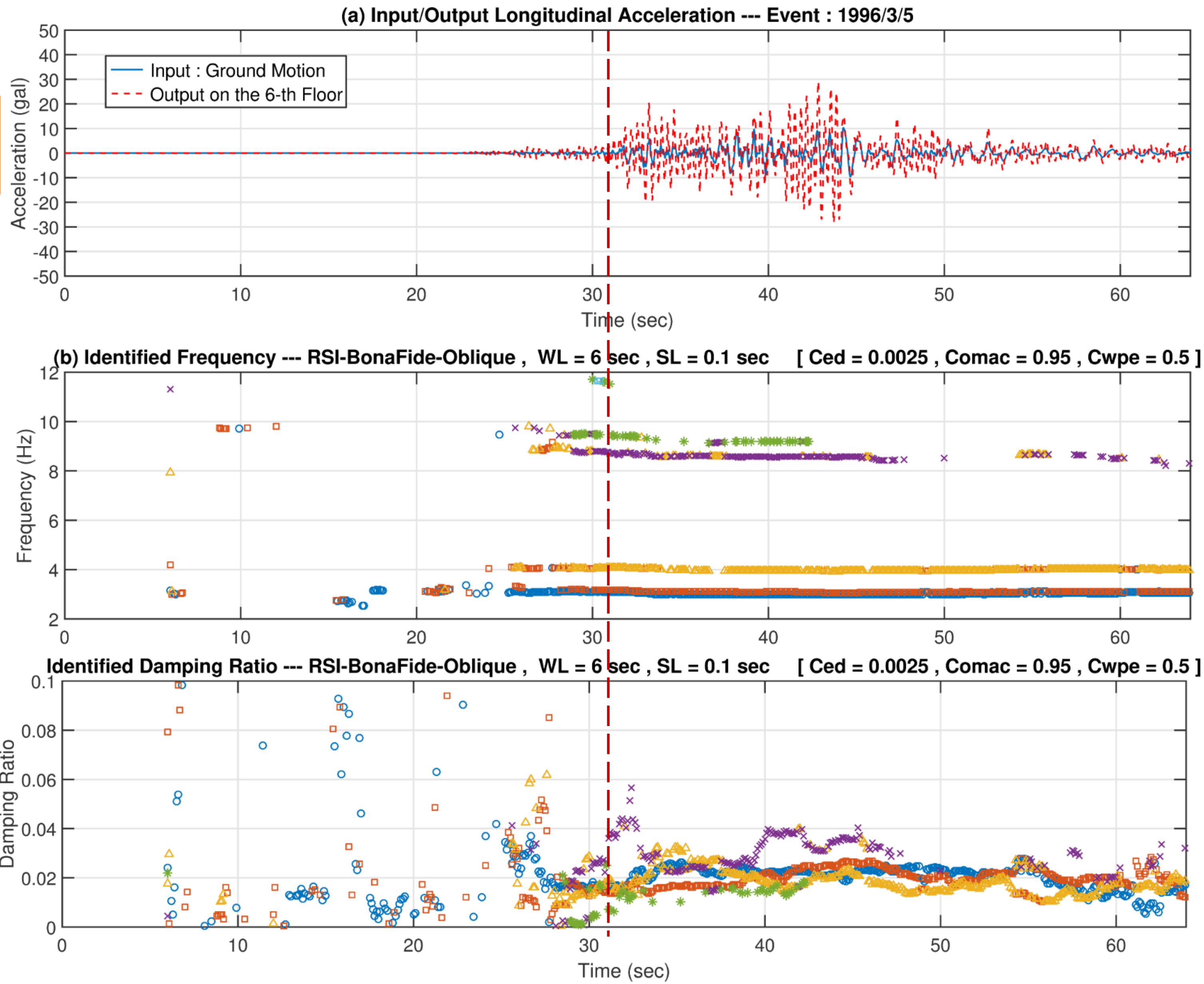
Damage Assessment of Building Structure Using RSI

1996-3-5 EQ

Measurements of small-scale event

Frequency (Hz)

Damping Ratio



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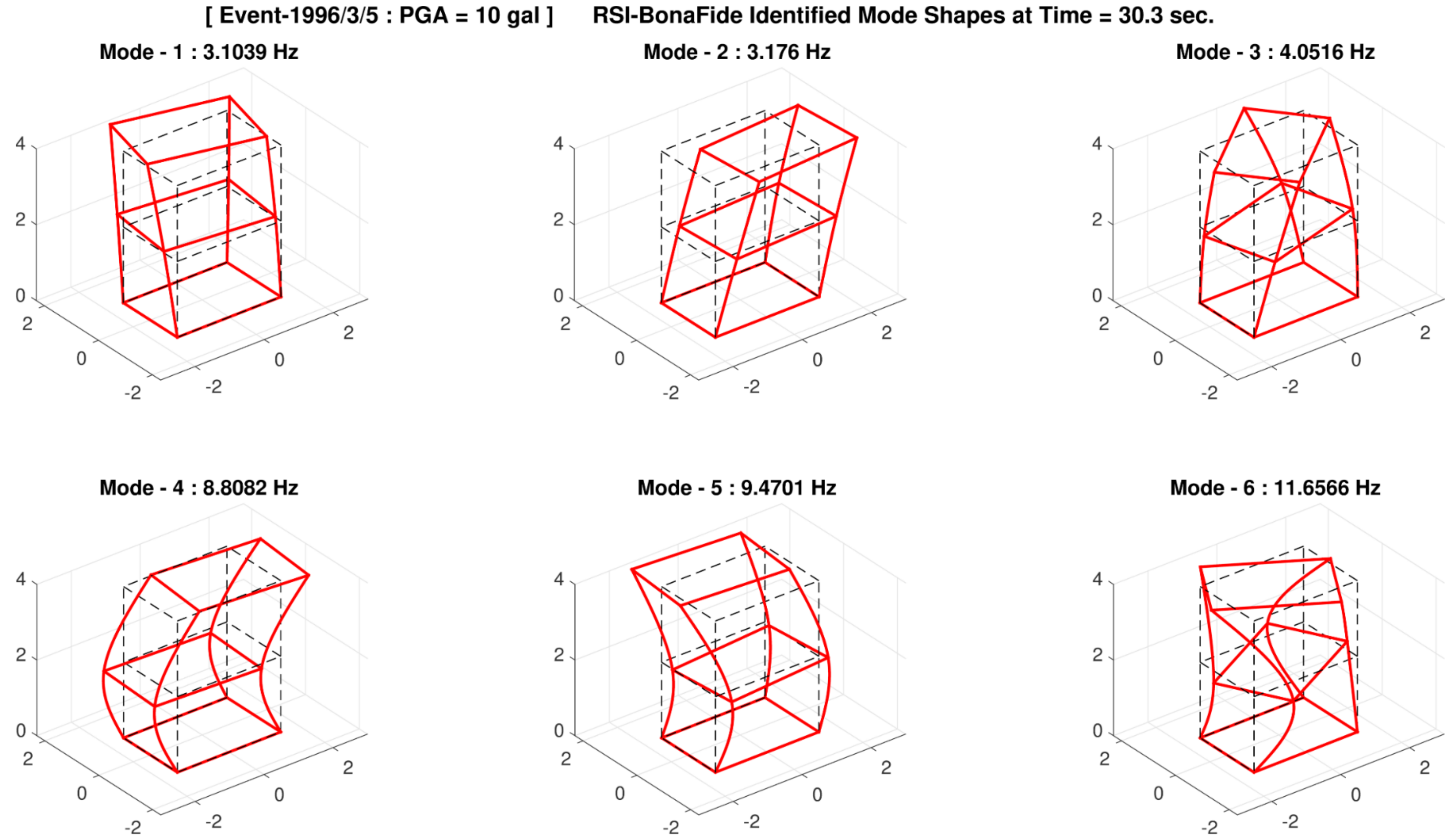
Mode Shapes at time = 30.3 sec. in the small-scale seismic event



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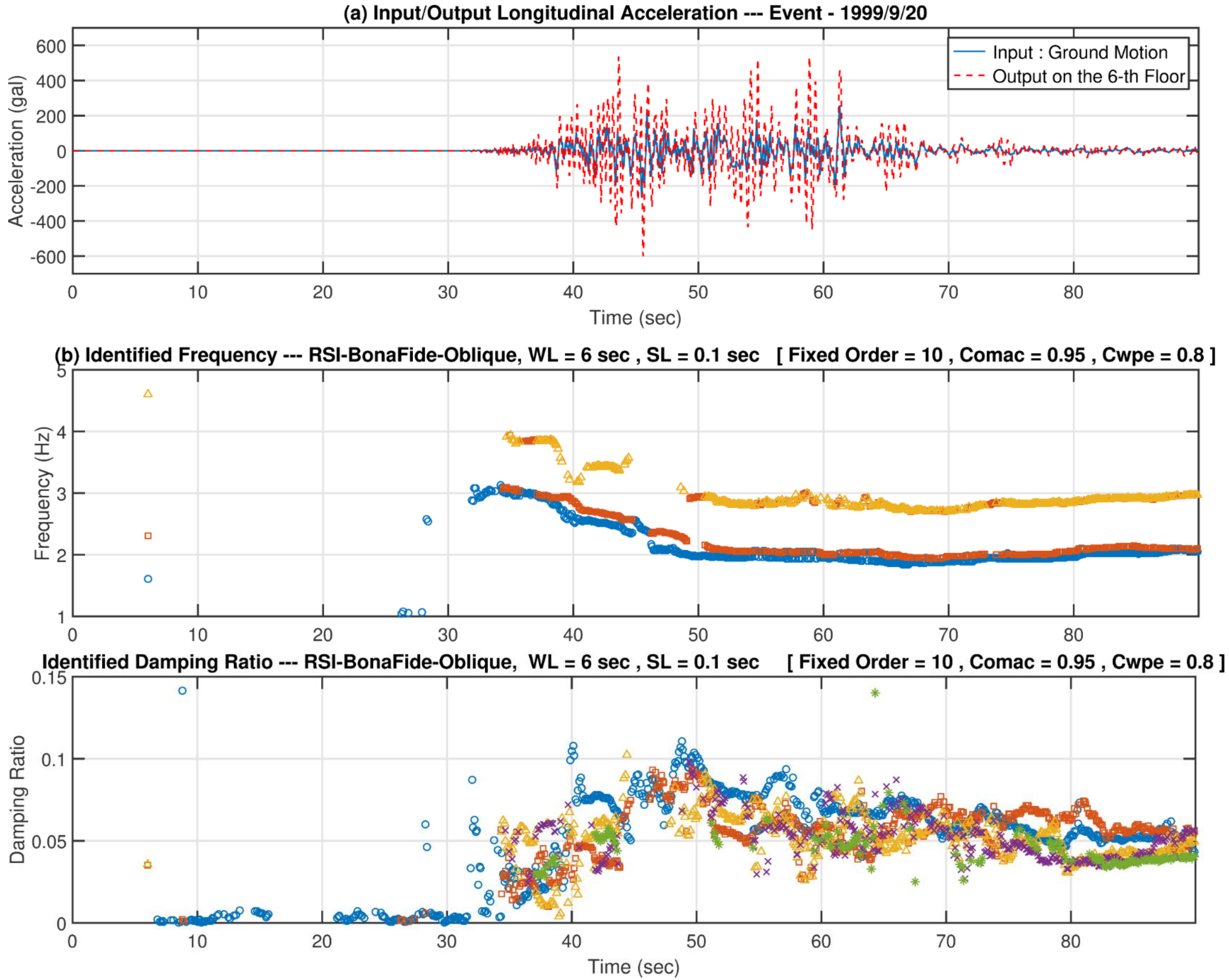
Damage Assessment of Building Structure Using RSI

1999-9-20 EQ

Measurements of Chi-Chi earthquake

Frequency (Hz)

Damping Ratio



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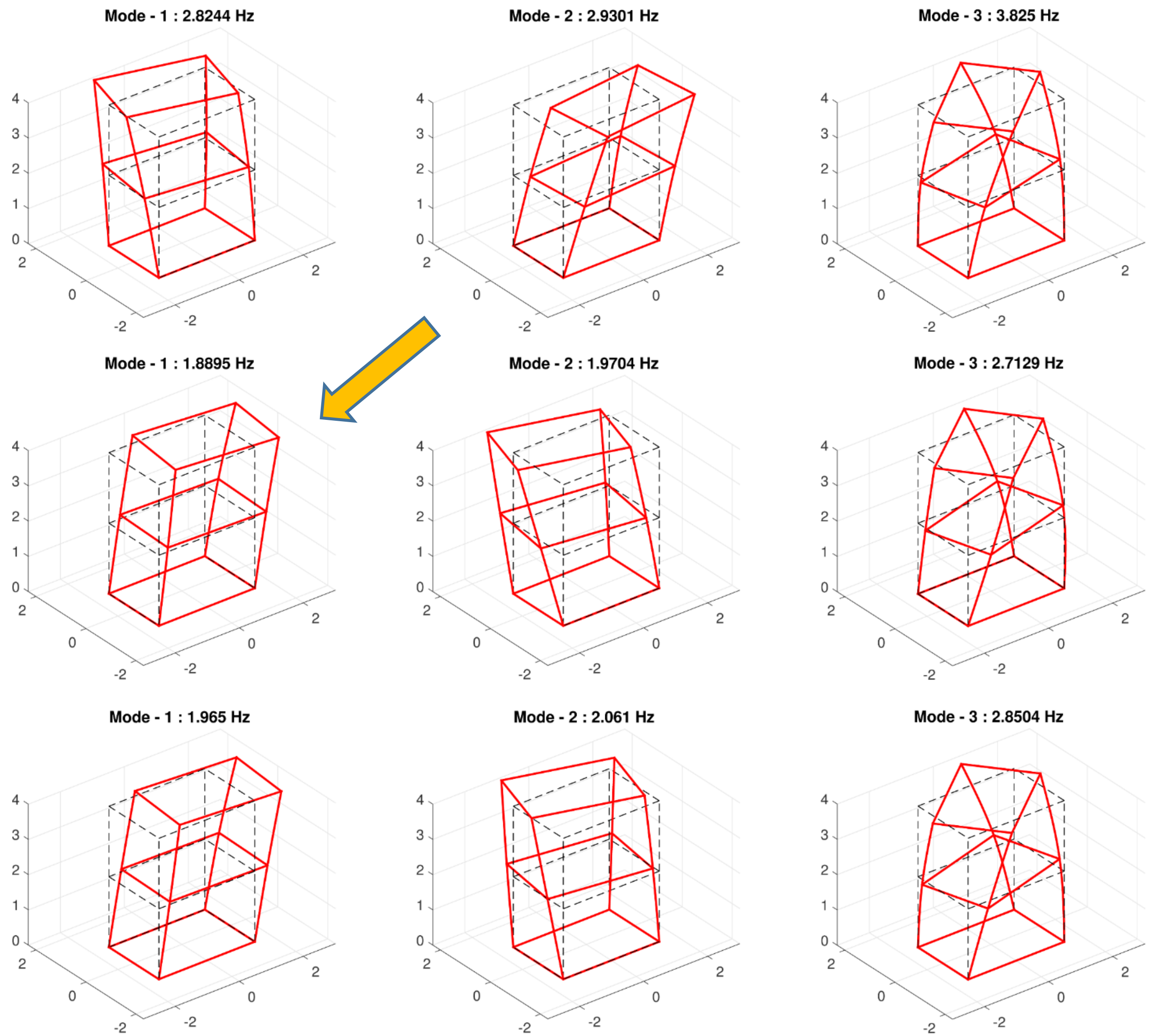
Damage Assessment of Building Structure Using RSI

Time at 38.5 sec.
(Before Strong Motion)

Time at 70.0 sec.
(After Strong Motion)

Time at 80.0 sec.
(After Strong Motion)



(1) Least Squares Stiffness Method (LSSM)

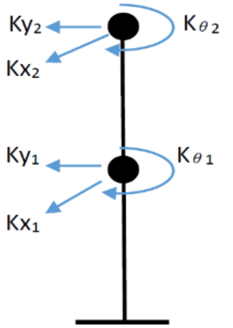
➢ **Once modal frequencies and mode shapes are identified by RSI-BonaFide, and information of mass is properly assumed…**

$$\mathbf{K}_{\text{System}}\boldsymbol{\Phi}_{\mathbf{r},(t=k)} = \omega^2_{r,(t=k)}\mathbf{M}_{\text{System}}\boldsymbol{\Phi}_{\mathbf{r},(t=k)}$$

$$\begin{bmatrix}\boldsymbol{\Lambda}_1\\ \boldsymbol{\Lambda}_2\\ \vdots\\ \boldsymbol{\Lambda}_s\end{bmatrix}_{(s\times n)\times n} \times \begin{bmatrix}k_1\\ k_2\\ k_3\\ \vdots\\ k_n\end{bmatrix}_{(n\times 1)} = \begin{bmatrix}\boldsymbol{\Lambda}_1\\ \boldsymbol{\Lambda}_2\\ \vdots\\ \boldsymbol{\Lambda}_s\end{bmatrix}_{(s\times n)\times 1}$$

$$k = \Delta^{-1}\Lambda$$

Least-squares Member stiffness



$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & \cdots & 0 & 0\\ 0 & m_2 & \cdots & 0 & 0\\ \vdots & \vdots & \ddots & \vdots & \vdots\\ 0 & 0 & \cdots & m_{n-1} & 0\\ 0 & 0 & \cdots & 0 & m_n \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} k_1+k_2 & -k_2 & & 0 & \\ -k_2 & k_2+k_3 & \ddots & & \\ & & \ddots & & \\ & \ddots & & k_{n-1}+k_n & -k_n\\ 0 & & & -k_n & k_n \end{bmatrix}$$

$$\boldsymbol{\Delta}_{\mathbf{r}} = \begin{bmatrix} \phi_{1,r} & \phi_{1,r}-\phi_{2,r} & 0 & & \cdots & 0\\ 0 & \phi_{2,r}-\phi_{1,r} & \phi_{2,r}-\phi_{3,r} & & \cdots & 0\\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots\\ 0 & 0 & \cdots & & \phi_{n-1,r}-\phi_{n-2,r} & \phi_{n-1,r}-\phi_{n,r}\\ 0 & 0 & \cdots & & 0 & \phi_{n,r}-\phi_{n-1,r} \end{bmatrix}$$

$$\boldsymbol{\Lambda}_{\mathbf{r}} = \omega^2_{(t=k),r} \times \begin{bmatrix} m_1\phi_{1,r}\\ m_2\phi_{2,r}\\ m_3\phi_{3,r}\\ \vdots\\ m_n\phi_{n,r} \end{bmatrix}$$

Modal parameter matrices

Ref: J. M. Caicedo, S.J. Dyke and E. A. Johnson. (2004),
Natural excitation technique and eigensystem realization algorithm for phase I of the IASC-ASCE benchmark problem: simulated data, Journal of Engineering Mechanics, Vol.130, No.1, p49-60.

(2) Efficient Model Correction Method (EMCM)

- Input:

(1) Nominal Mass & Stiffness Matrix

(2) Modal Frequencies & Mode Shapes

Efficient Model Correction Method (EMCM)

Constructing the M-orthogonal basis vectors : G matrix

(Gram-Schmidt orthogonalization process for unmeasured mode shapes v_r^*)

$$G = \begin{cases} g_r = \Phi_{(k),r} & , r = 1,2,\dots,s \\ g_r = v_r^* & , r = s+1,\dots,N_{total\_DOFs} \end{cases}$$

Calculating the inverse of transformation matrix : R^{-1} matrix

$$R^{-1} = G \cdot \left[\hat{\Phi}_{(k),1} \quad \hat{\Phi}_{(k),2} \quad \cdots \quad \hat{\Phi}_{(k),s} \quad g_{s+1} \quad \cdots \quad g_{otal\_DOFs}\right]^{-1}$$

Correcting the mass matrix : M^{update} matrix

$$M^{update} = (R^{-1})^T \cdot M \cdot R^{-1}$$

Pre-correcting the stiffness matrix : K^* matrix

$$K^* = (R^{-1})^T \cdot K \cdot R^{-1}$$

Correcting the stiffness matrix : K^{update} matrix

$$K^{update} = K^* + M^{update} \cdot \left[\sum_{r=1}^{s} (\hat{\omega}_r^2 - \omega_r^2) \cdot \hat{\Phi}_{(k),r} \cdot \hat{\Phi}_{(k),r}^{\;T}\right] \cdot M^{update}$$

- Output:

Updated Mass & Stiffness Matrix

(1) Symmetry of updated matrices

$$M_{update} = M_{update}^T$$
$$K_{update} = K_{update}^T$$

(2) Orthogonality of updated matrices

$$\Phi_{r,update}^T \cdot M_{update} \cdot \Phi_{p,update} = \delta_{r,p}$$
$$\Phi_{r,update}^T \cdot K_{update} \cdot \Phi_{p,update} = \begin{cases} \hat{\omega}_r^2 \cdot \delta_{r,p} \\ \omega_r^2 \cdot \delta_{r,p} \end{cases}$$

(3) Satisfaction of Eigen-equation [Model Error = 0]

$$K_{update} \cdot \hat{\Phi}_r - \hat{\omega}_r^2 \cdot M_{update} \cdot \hat{\Phi}_r = 0$$

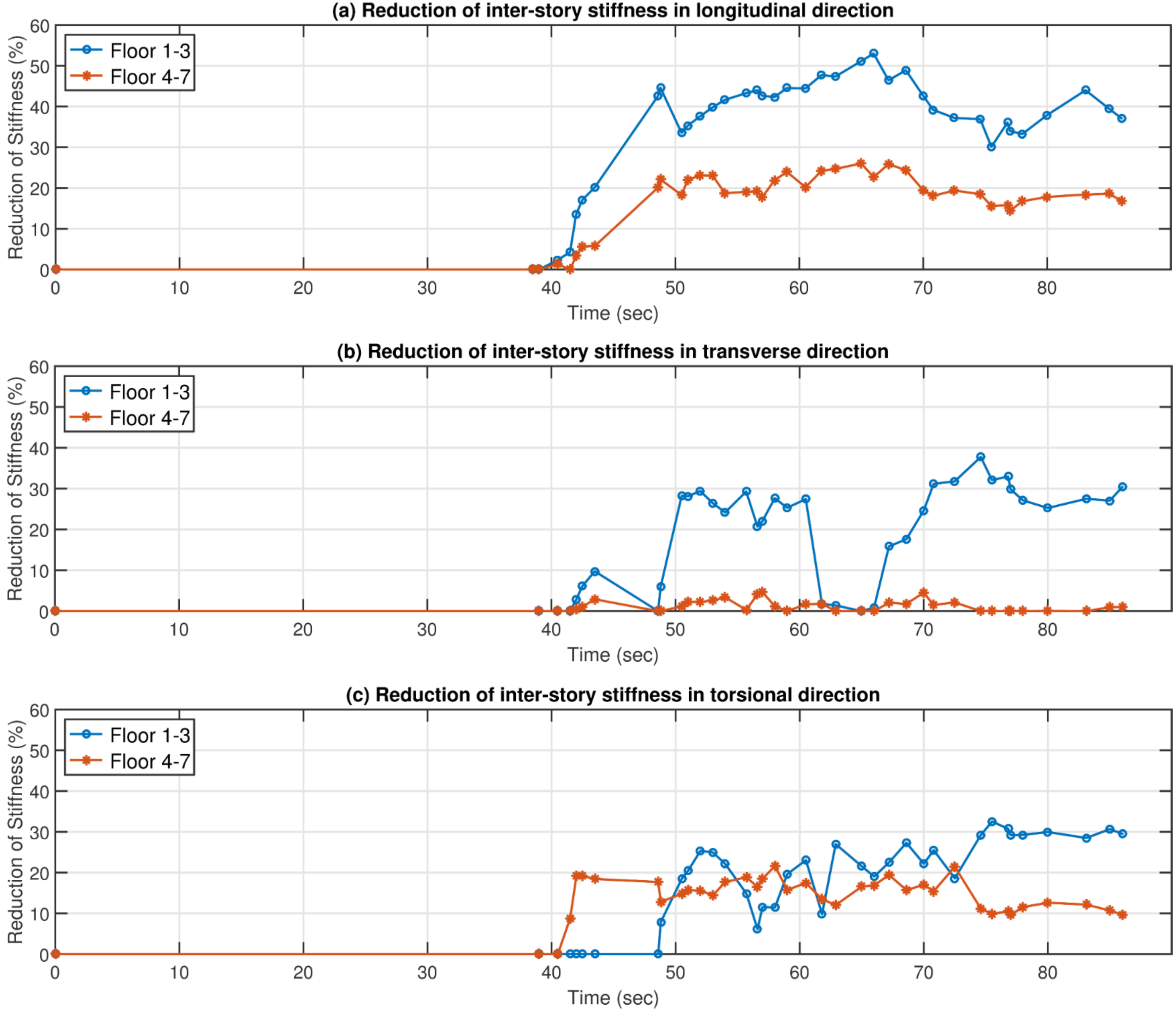
Ref: K.V. Yuen, "Efficient model correction method with modal measurement," Journal of Engineering Mechanics, Vol. 136, No. 1, 91-99 (2010).

Damage Assessment of Building Structure Using RSI

Reduction of Longitudinal Stiffness (%)

Reduction of Transverse Stiffness (%)

Reduction of Torsional Stiffness (%)



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Estimation of Computation Time

Computational Time per Identification using traditional LQ decomposition						
RSI-Procedure	**Preprocess**	**Projection (Oblique)**	**Eigen-value Decomp.**	**Parameter Extraction**	**Computational Time**	
Mean (sec.)	0.0194	0.0192	0.0249	0.0046	μ	0.0681
STD (sec.)	0.0104	0.0025	0.0041	0.0011	$\mu+2\sigma$	0.1043

Computational Time per Identification using RSI-BonaFide-OBL						
RSI-Procedure	**Preprocess**	**Projection (Oblique)**	**Eigen-value Decomp.**	**Parameter Extraction**	**Computational Time**	
Initial Conduction	0.0194	0.0252	0.0101	0.0061	0.0608	
Updating Method	*Bona-Fide L32 renewing algorithm*					
Mean (sec.)	0.0194	0.0050	0.0251	0.0046	μ	0.0541
STD (sec.)	0.0104	0.0005	0.0043	0.0012	$\mu+2\sigma$	0.0869

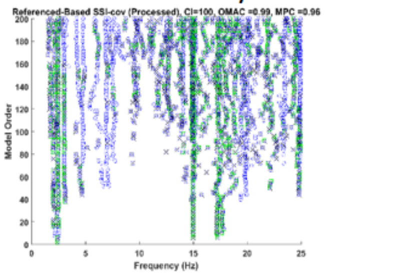
Computational Time per Identification using RSI-Inversion-OBL						
RSI-Procedure	**Preprocess**	**Projection (Oblique)**	**Eigen-value Decomp.**	**Parameter Extraction**	**Computational Time**	
Initial Conduction	0.0194	0.3149	0.0314	0.0129	0.3786	
Updating Method	*Inversion-Oblique Projection renewing algorithm*					
Mean (sec.)	0.0194	0.0032	0.0259	0.0048	μ	0.0533
STD (sec.)	0.0104	0.0004	0.0041	0.0016	$\mu+2\sigma$	0.0863

Less Than Shifting Length = 0.1 sec

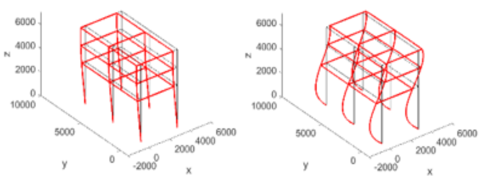
NCREE-South Center Grand Opening Shaking Table Test

WN1-test

SSI-COV analysis

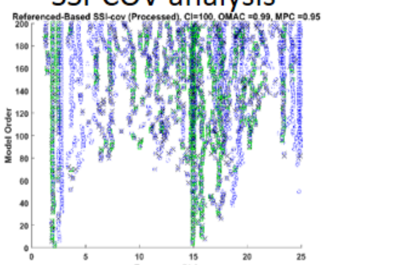


mode 1: Freq = 2.517Hz, Damp. Ratio = 6.692%   mode 2: Freq = 14.979Hz, Damp. Ratio = 1.752%

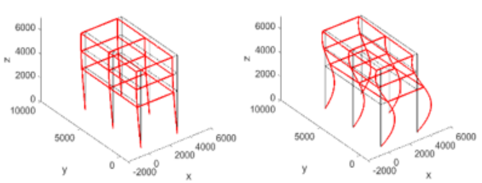


WN2-test

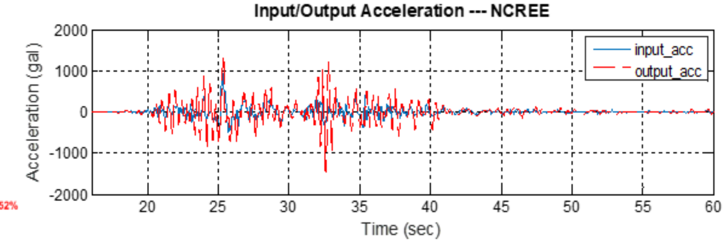
SSI-COV analysis

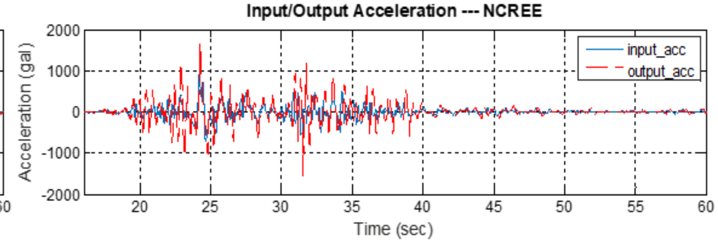


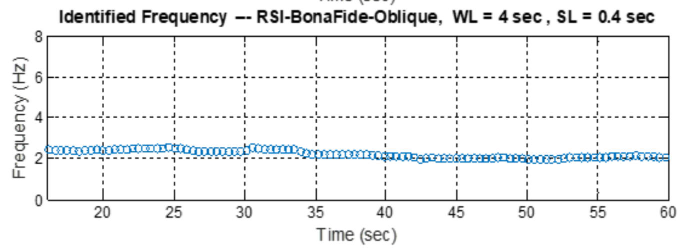
mode 1: Freq = 1.949Hz, Damp. Ratio = 7.440%   mode 2: Freq = 15.001Hz, Damp. Ratio = 0.545%

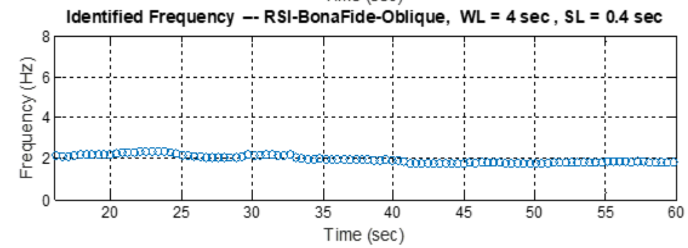


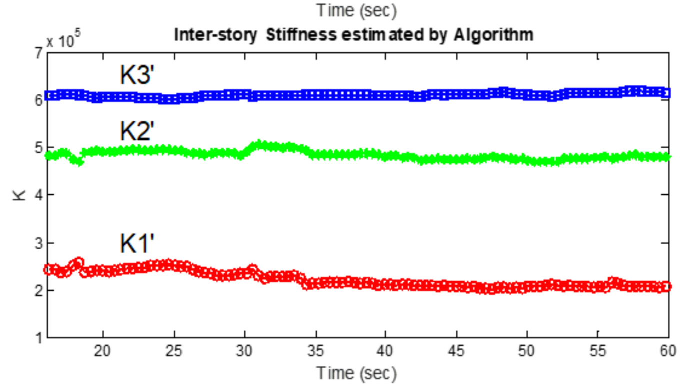
WN1-test → 1st Test, Input:TCU052 (PGA=800 gal) → WN2-test → 2st Test, Input:TCU052 (PGA=1000 gal)

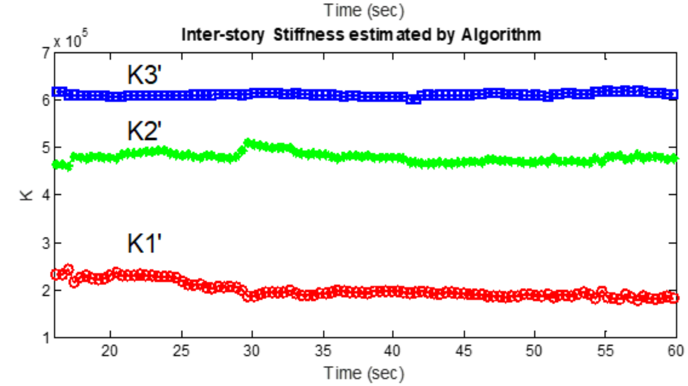






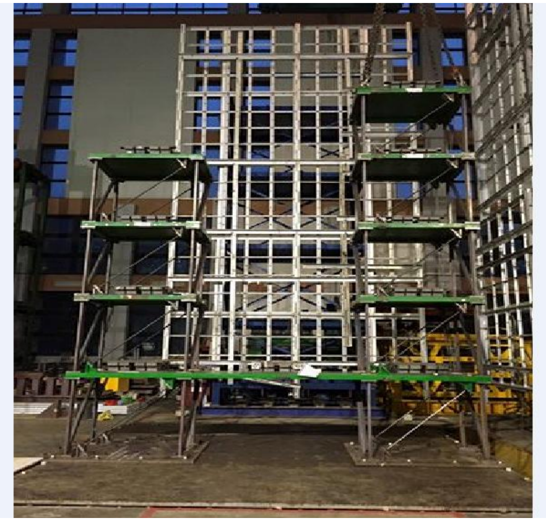


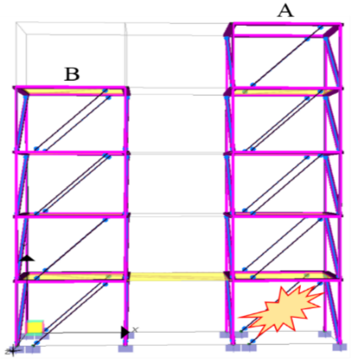




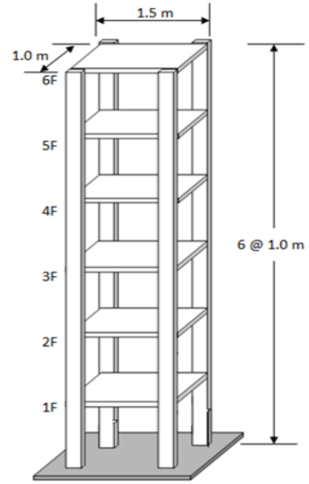
NCREE-South Test	Estimated stiffness (KN/m)			
	Initial	Minimum	Final	% of reduction
800 gal excitation	2.28×10^4	1.87×10^4	1.93×10^4	15.4%
1000 gal excitation	2.18×10^4	1.66×10^4	1.71×10^4	21.6% (25%)

Damage Detection & Localization

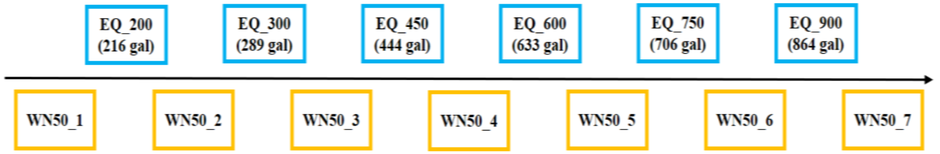




(a) Weak bracing at the 1st FL of A.



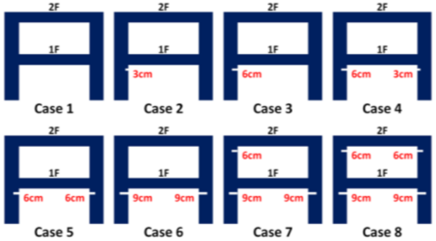
Brace1 Dimension: 19 mm × 1.2 mm (weak)
Brace2 Dimension: 21.3 mm × 2 mm (normal)
Dimension of each floor: 1.1 m × 1.5 m × 1.17 m



Floor	Damage Cases							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
6th FL	Original Un-damaged Case	-	-	-	-	-	-	-
5th FL		-	-	-	-	-	-	-
4th FL		-	-	-	-	-	-	-
3rd FL		-	-	-	-	-	-	-
2nd FL		-	-	-	-	-	Cut a_6	Cut a_6 and b_6
1st FL		Cut a_3	Cut a_6	Cut a_6 and b_3	Cut a_6 and b_6	Cut a_9 and b_9	Cut a_9 and b_9	Cut a_9 and b_9

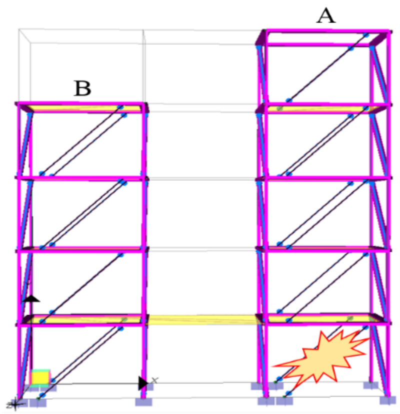
Structure damaged in Lower modes

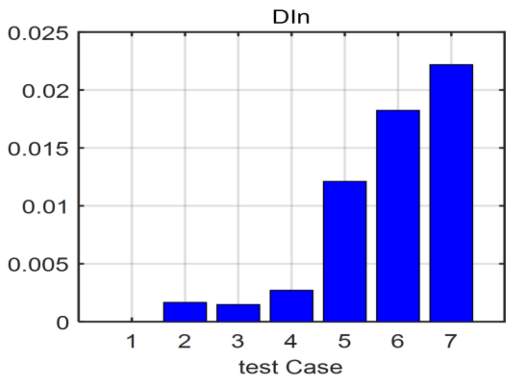
Structure damaged in higher modes

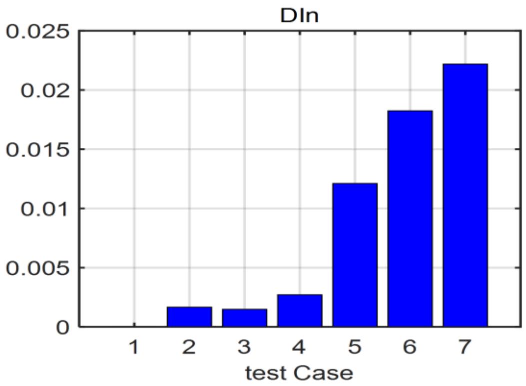


Results from SSI-COV (ambient data)

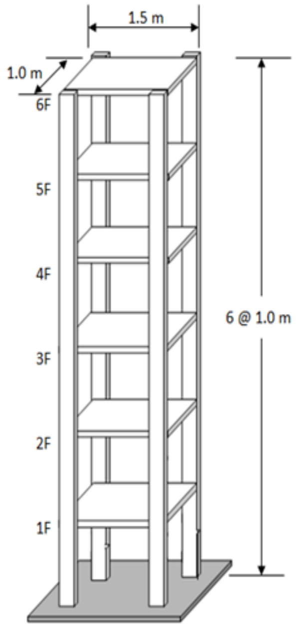
Freq.(Hz)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Mode 1	4.917	4.899	4.896	4.872	3.251	2.329	1.744
Mode 2	7.133	7.112	7.143	7.130	6.655	6.559	6.502
Mode 3	15.434	15.398	15.418	15.326	11.860	11.056	10.646
Mode 4	20.770	20.782	20.757	20.748	20.362	20.417	20.224
Mode 5	21.843	21.749	21.855	21.768	21.252	21.010	22.399
Mode 6	27.817	27.817	27.712	27.780	27.782	27.464	27.238
Mode 7	33.775	33.655	32.647	32.868	32.823	32.745	38.072
Mode 8	38.511	38.028	37.750	37.597	37.631	37.760	34.574
Mode 9	39.978	39.534	38.361	38.422	39.198	38.966	38.864



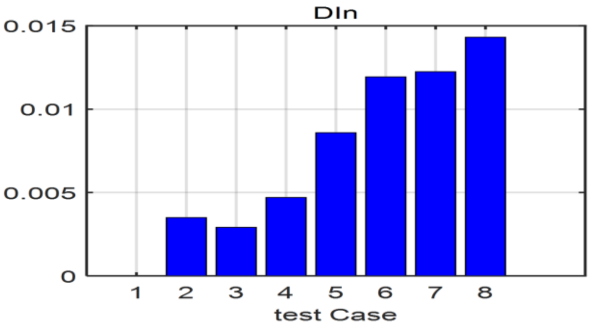


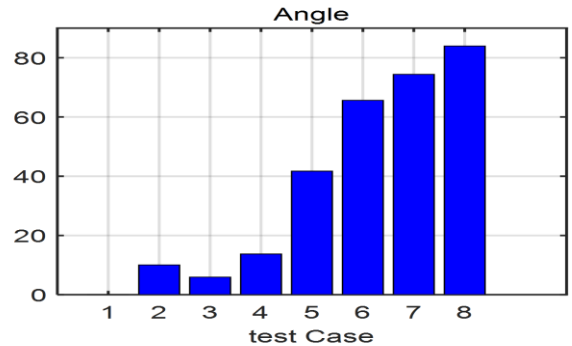


Results from SSI-COV (ambient data)



Freq.(Hz)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Mode 1	1.141	1.139	1.137	1.136	1.138	1.133	1.131	1.129
Mode 2	2.224	2.211	2.203	2.200	2.201	2.197	2.190	2.187
Mode 3	3.632	3.628	3.615	3.612	3.602	3.587	3.579	3.576
Mode 4	6.299	6.295	6.283	6.277	6.267	6.248	6.245	6.244
Mode 5	8.516	8.478	8.463	8.466	8.458	8.451	8.410	8.380
Mode 6	9.189	9.184	9.169	9.162	9.146	9.105	9.091	9.078
Mode 7	10.450	10.420	10.390	10.403	10.399	10.395	10.336	10.309
Mode 8	12.065	12.064	12.049	12.041	12.032	11.979	11.950	11.933
Mode 9	14.313	14.309	14.299	14.297	14.295	14.282	14.265	14.245
Mode 10	19.821	19.733	19.631	19.582	19.471	19.125	19.010	18.917
Mode 11	21.949	21.860	21.783	21.753	21.665	21.446	21.355	21.355
Mode 12	27.961	27.954	27.974	27.975	28.019	28.116	28.117	28.114
Mode 13	38.407	38.240	37.914	37.794	37.525	37.054	36.931	36.954
Mode 14	58.419	58.233	57.598	57.294	56.573	54.786	53.778	51.835
Mode 15	60.134	59.917	59.660	59.529	59.494	59.422	59.281	59.225
Mode 16	76.283	76.249	75.989	75.944	75.801	75.289	74.380	73.502
Mode 17	77.928	77.781	77.221	77.143	76.920	76.668	76.682	76.598





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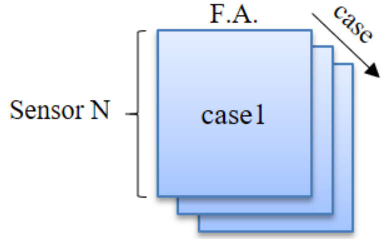
Damage detection & Localization : Sammon Map

Step 1: Create X matrix (consider to be N-dimensional space)

$$[X] = \begin{bmatrix} sensor\ 1(x) \\ sensor\ 2(x) \\ \vdots \\ sensor\ M(x) \end{bmatrix}_{M\times N}$$



where M is the number of sensing nodes, N is the number of discrete Fourier amplitude. (Time domain data can also be applied.)

Step 2: Covariance matrix

$$[C]_{M\times M} = cov(X) = \frac{XX^T}{M-1} \quad \Rightarrow \quad C = \Phi\Lambda\Phi^T$$

Step 3: Solve for the eigenvalue, eigenvectors of *C*

$$[\Lambda] = diag(\lambda_1, \lambda_2, \dots, \lambda_M) \quad \text{where } \lambda_1 > \lambda_2 > \cdots > \lambda_M$$

Step 4a: Project the high-dimensional space onto the 2-D dimensional space

$$[X]_{2D-PCA} = X \cdot [\Phi(\lambda_1, \lambda_2)]$$ ← 2D-PCA matrix

$$[X]_{2D-PCA} = \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \\ \vdots & \vdots \\ x_{M1} & x_{M2} \end{bmatrix}$$

Euclidean distance:

$$\delta_{Xi,j} = \sqrt{\sum_{p=1}^{2}(X_{i,p} - X_{j,p})^2}$$

to construct the initial PCA-based map

$$[\Delta_{PCA-map}]_{M\times M} = \begin{bmatrix} 0 & \delta_{X1,2} & \cdots & \delta_{X1,M} \\ \delta_{X2,1} & 0 & \cdots & \delta_{X2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{XM,1} & \delta_{XM,2} & \cdots & 0 \end{bmatrix}_{M\times M}$$

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Damage detection & Localization : Sammon Map

Step 4b: To construct the $[X_{Sammon-Map}]_{48\times 2}$

Using $[X] = \begin{bmatrix} sensor\ 1(f) \\ sensor\ 2(f) \\ \vdots \\ sensor\ M(f) \end{bmatrix}_{M\times N}$

$\varepsilon_{Xi,j} = \sqrt{\sum_{k=1}^{N}([X_{i,k}] - [X_{j,k}])^2/N}$

to construct the initial $\{X\}$-based map

$$[\Delta_{\{X\}}]_{M\times M} = \begin{bmatrix} 0 & \varepsilon_{X1,2} & \cdots & \varepsilon_{X1,M} \\ \varepsilon_{X2,1} & 0 & \cdots & \varepsilon_{X2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{XM,1} & \varepsilon_{XM,2} & \cdots & 0 \end{bmatrix}_{M\times M}$$

Step 5: Minimization

From step 4b : $[\Delta_{\{X\}}]_{M\times M} = \begin{bmatrix} 0 & \varepsilon_{X1,2} & \cdots & \varepsilon_{X1,M} \\ \varepsilon_{X2,1} & 0 & \cdots & \varepsilon_{X2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{XM,1} & \varepsilon_{XM,2} & \cdots & 0 \end{bmatrix}_{M\times M}$

From step 4a $[\Delta_{PCA-map}]_{M\times M} = \begin{bmatrix} 0 & \delta_{X1,2} & \cdots & \delta_{X1,M} \\ \delta_{X2,1} & 0 & \cdots & \delta_{X2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{XM,1} & \delta_{XM,2} & \cdots & 0 \end{bmatrix}_{M\times M}$

$$E = \frac{1}{\sum_{i<j}\varepsilon_{Xi,j}} \sum_{i<j} \frac{(\varepsilon_{Xi,j} - \delta_{Xi,j})^2}{\varepsilon_{Xi,j}}$$

⇒ Minimization

Then we can get the reduce matrix :

$$[X]_{Sammon\ Map} = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_M & y_M \end{bmatrix}$$

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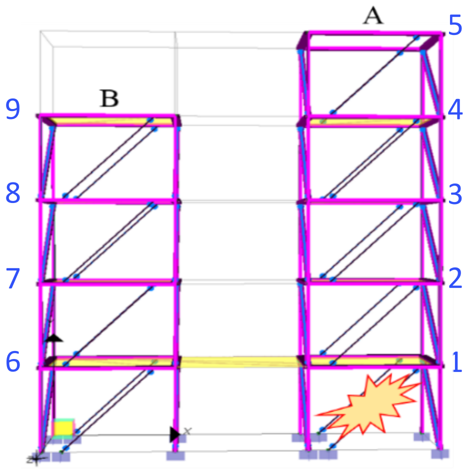
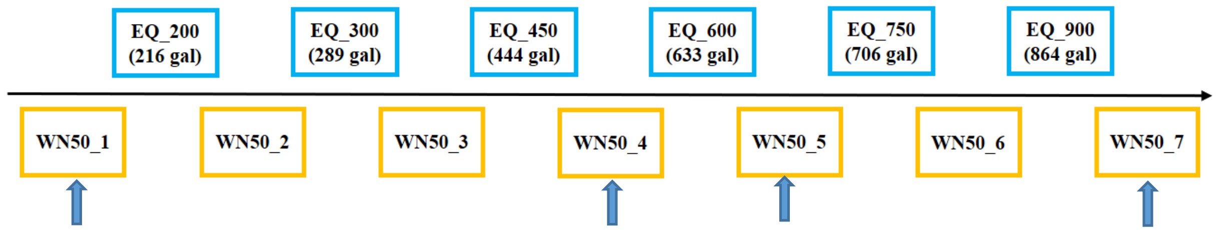
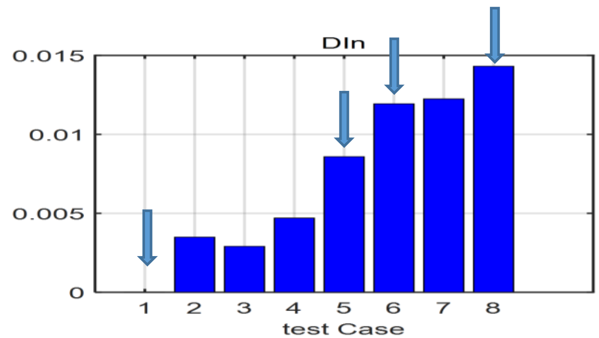
Damage detection & Localization : Sammon Map



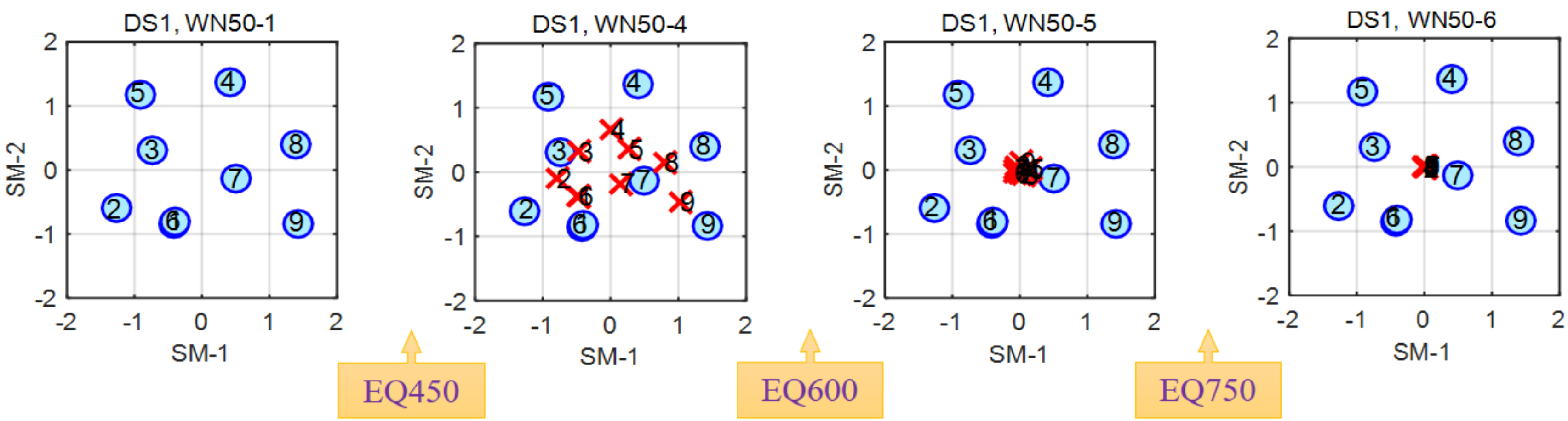
Damage Scenario 1



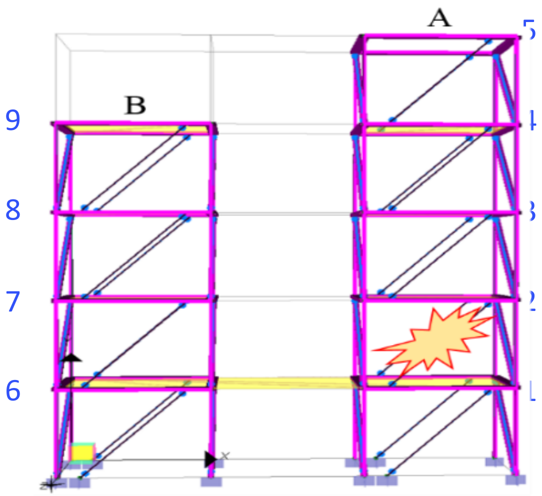


Scenario 1

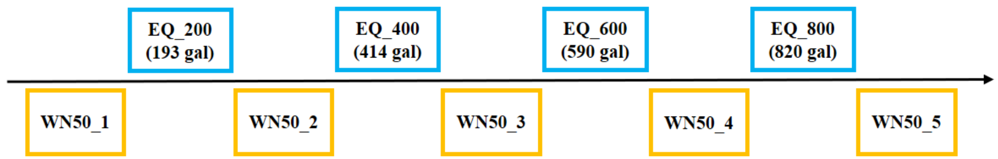
Reference

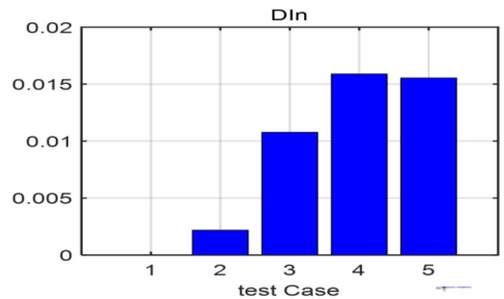


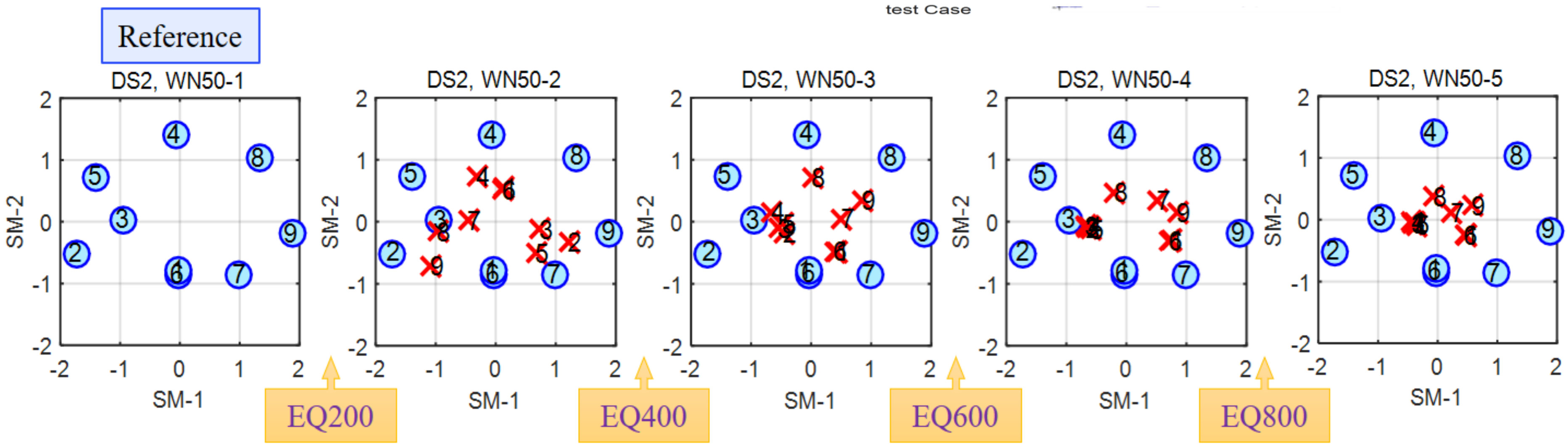
Damage detection & Localization : Sammon Map



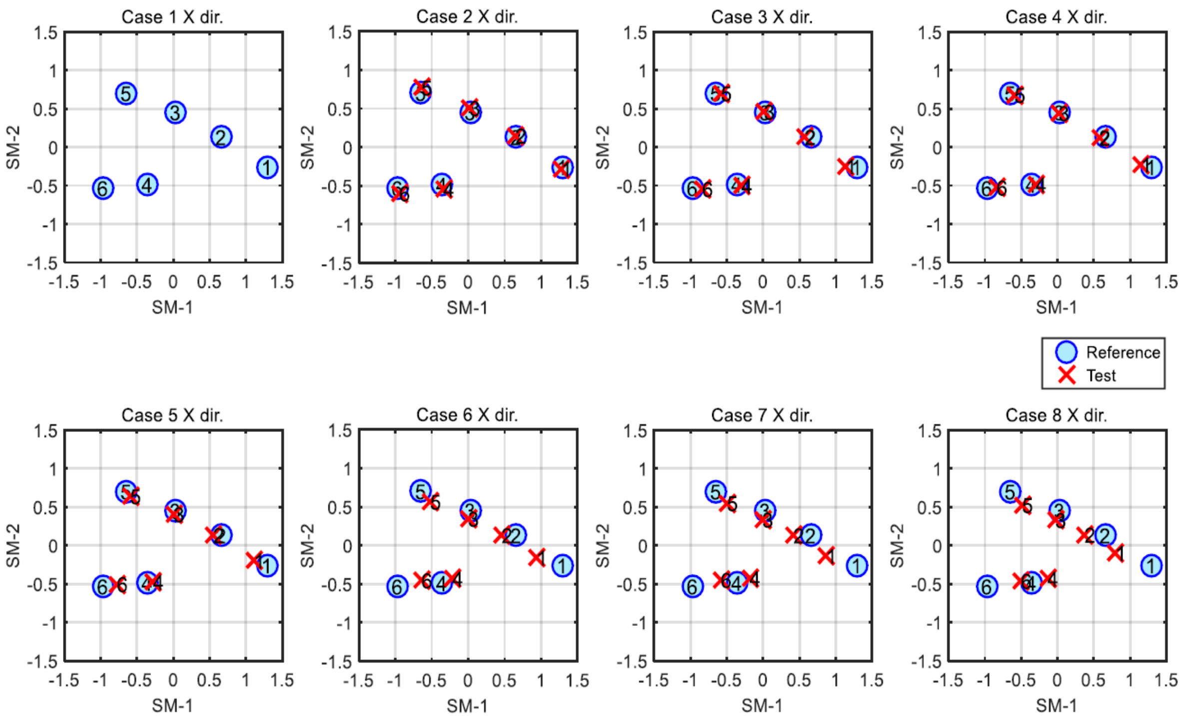
Damage Scenario 2

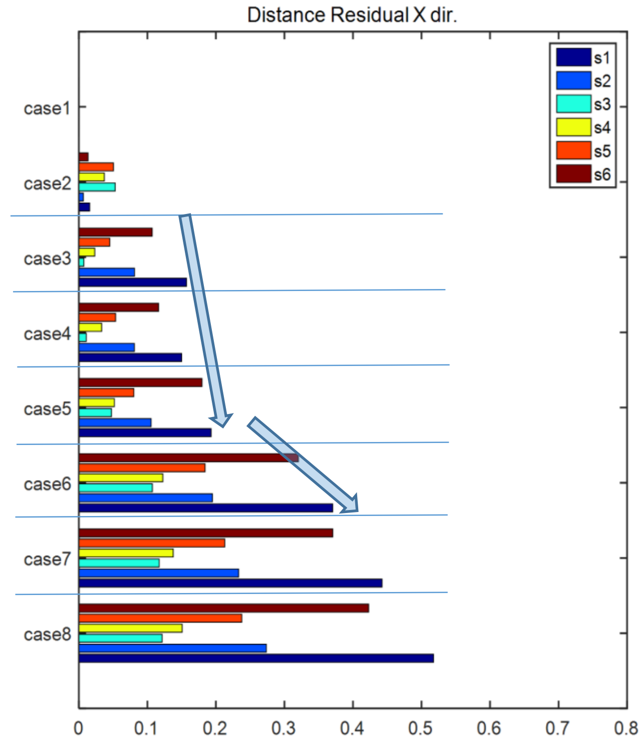


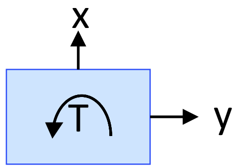


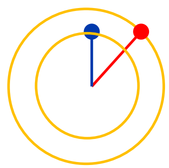


Damage detection & Localization : Sammon Map









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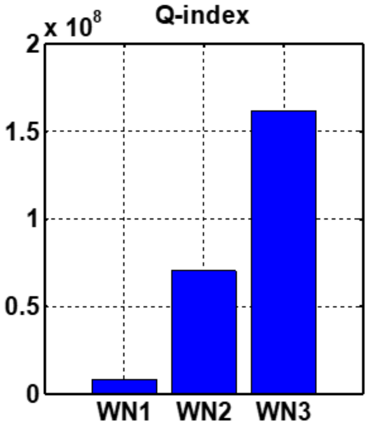
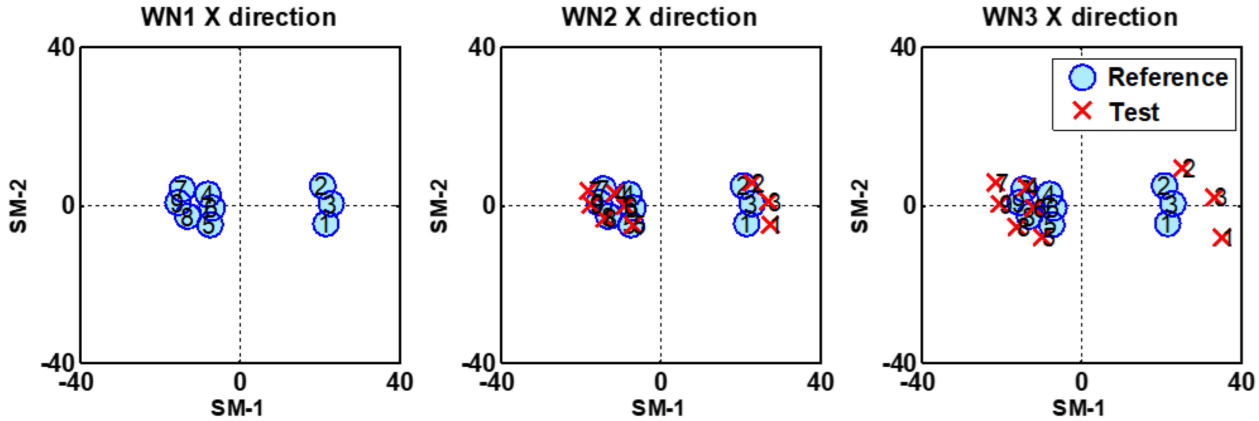
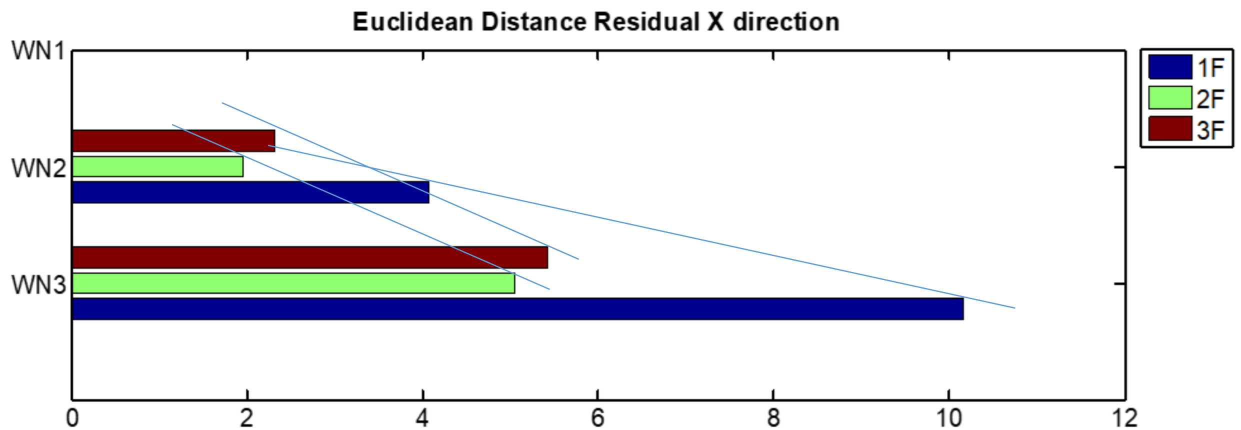
NCREE-South Center Grand Opening Ambient Vibration Test

WN1-test → 1st Test (Input:TCU052 (PGA=800 gal)) → WN2-test → 2nd Test (Input:TCU052 (PGA=1000 gal)) → WN3-test

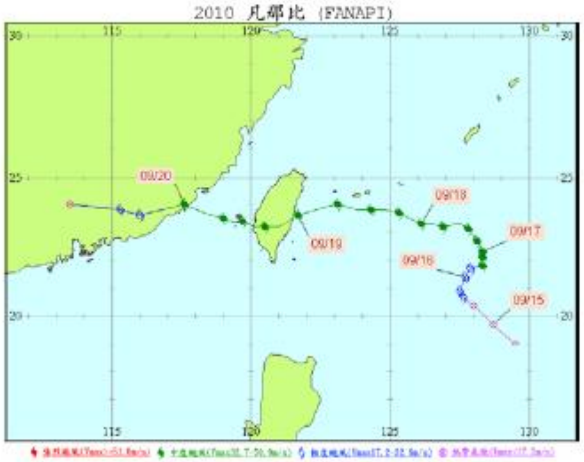


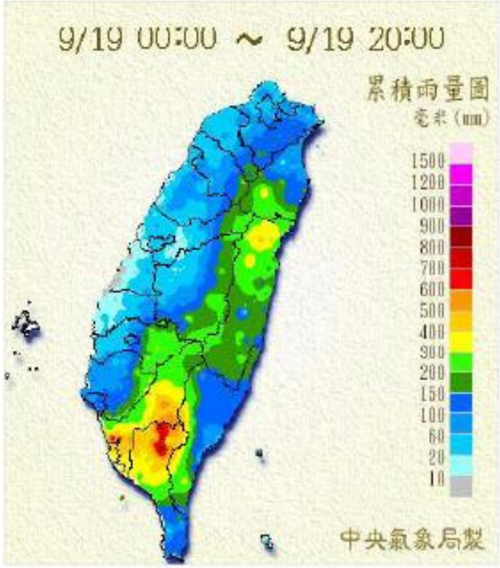
WN - Sammon map





Damage Assessment of Bridge Under Scouring Process





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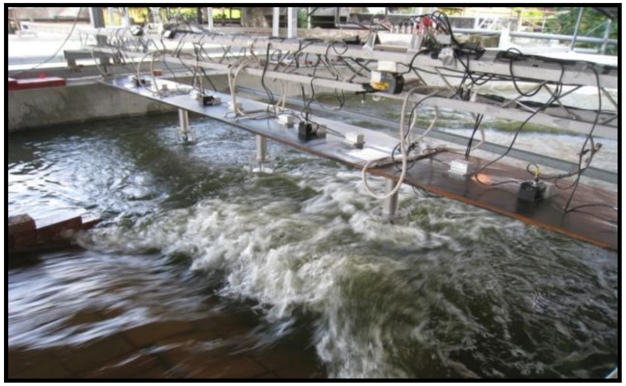
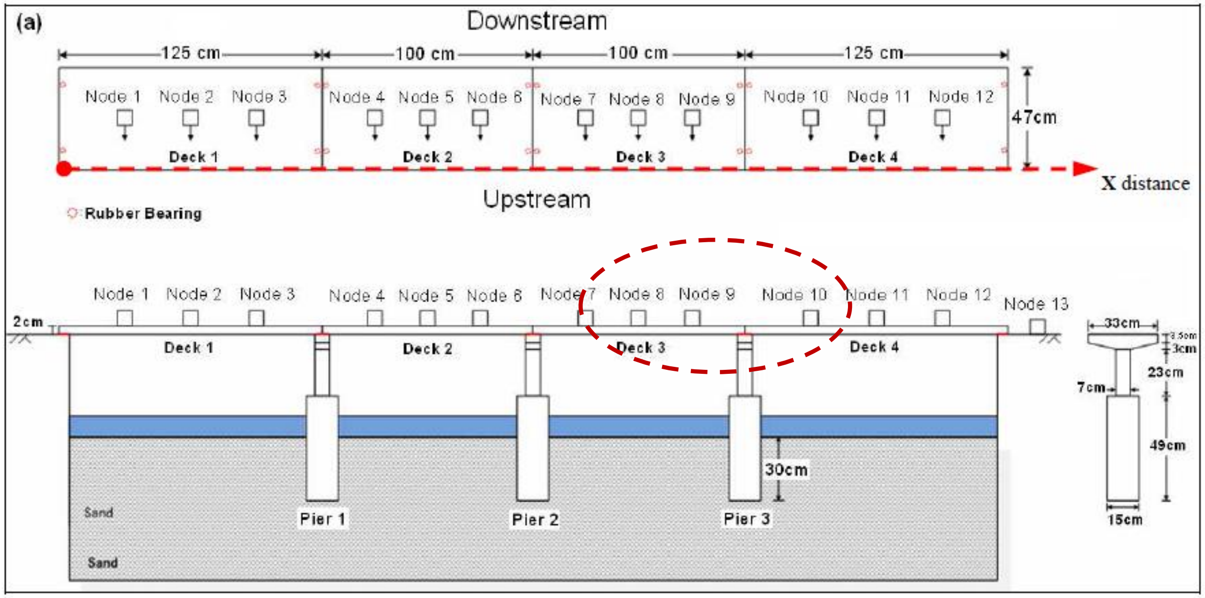
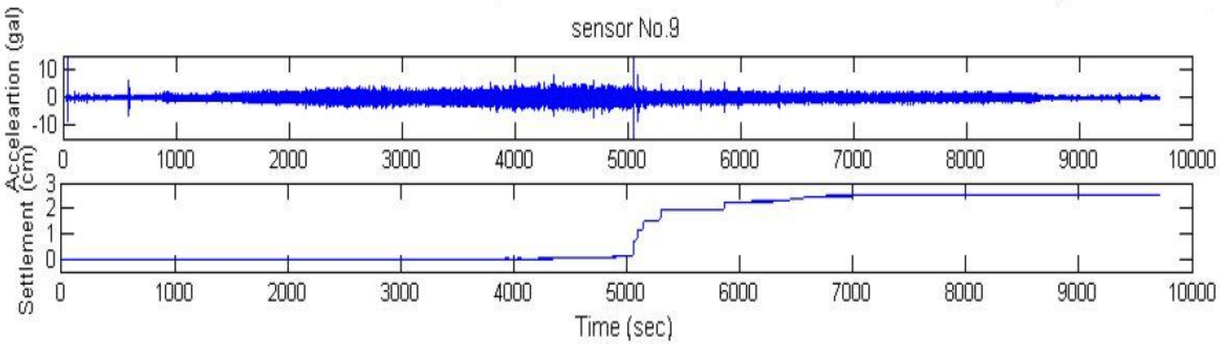
Damage Assessment of Bridge Under Scouring Process







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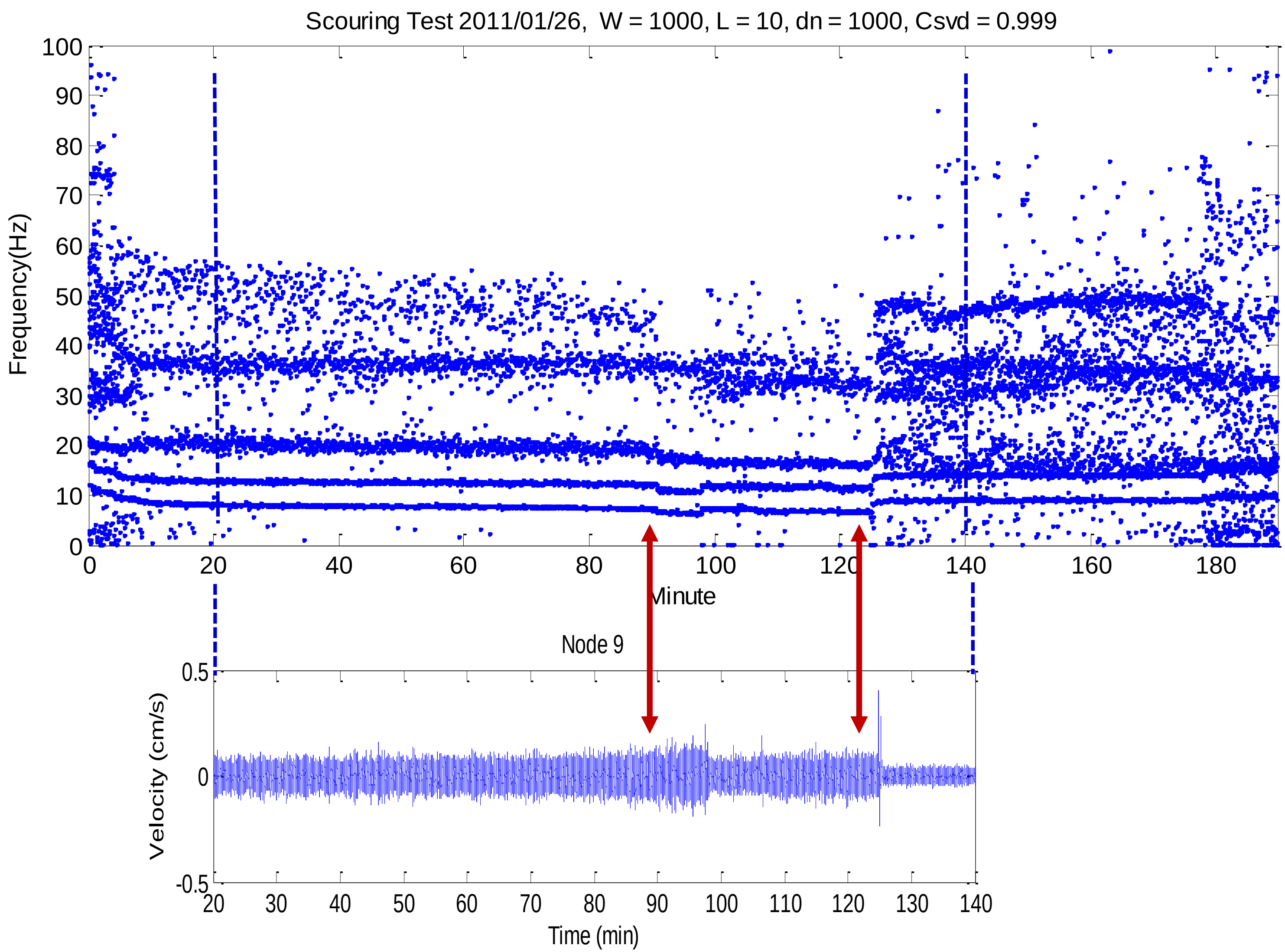
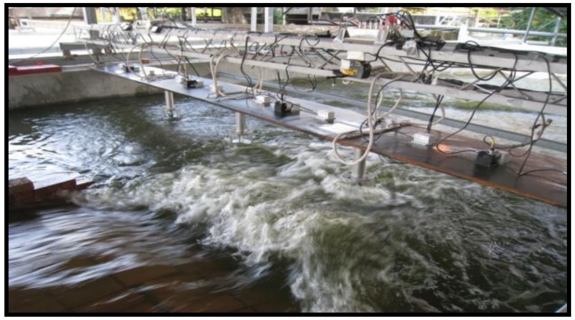
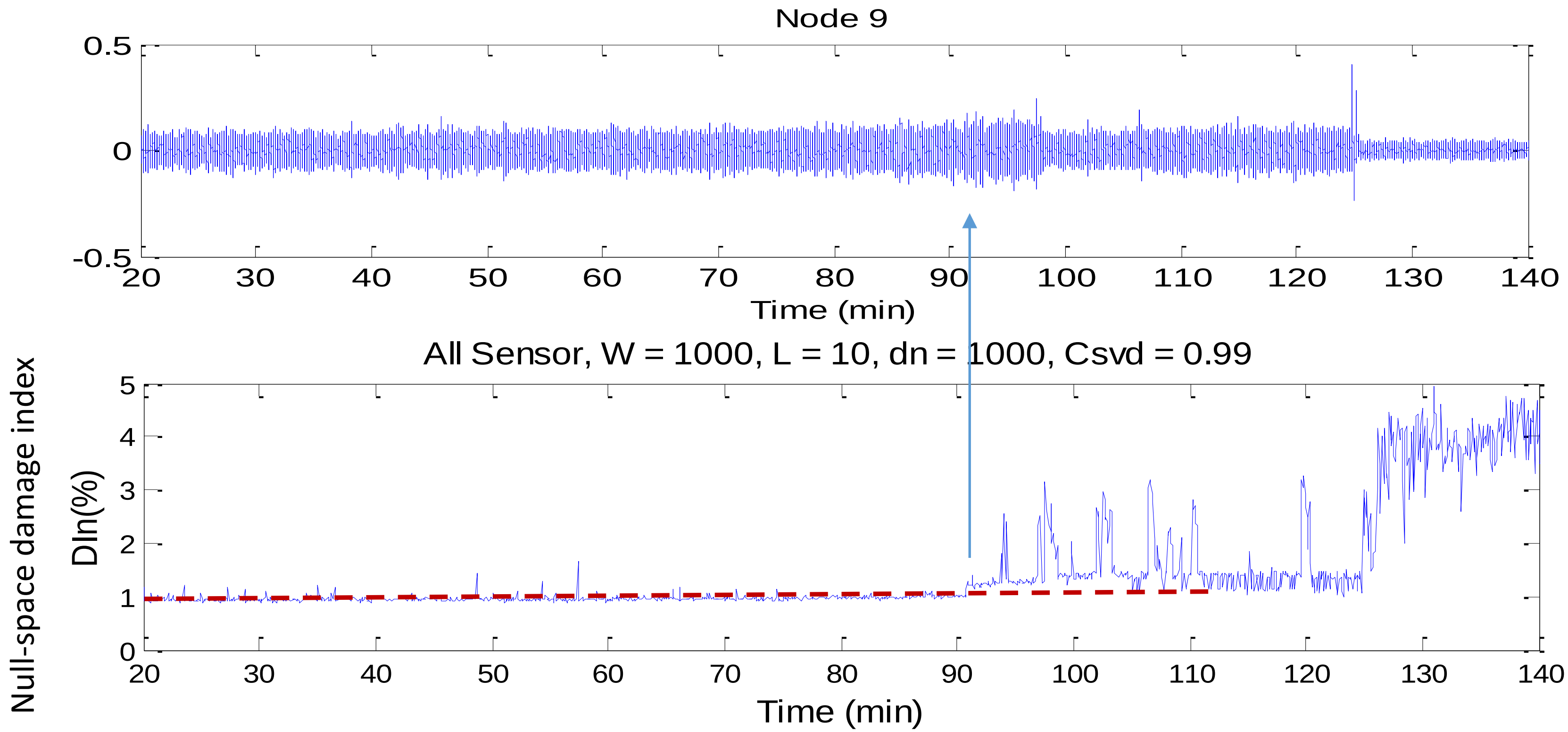
Moving window SSI-COV (using velocity data)



Damage Detection Algorithms: Results from DI_N & DI_S (scouring test)



$$DI_n = mean\{|\mathbf{U}_{\mathbf{n0}}^{\mathbf{T}}\mathbf{U}_{\mathbf{s}}|\}$$



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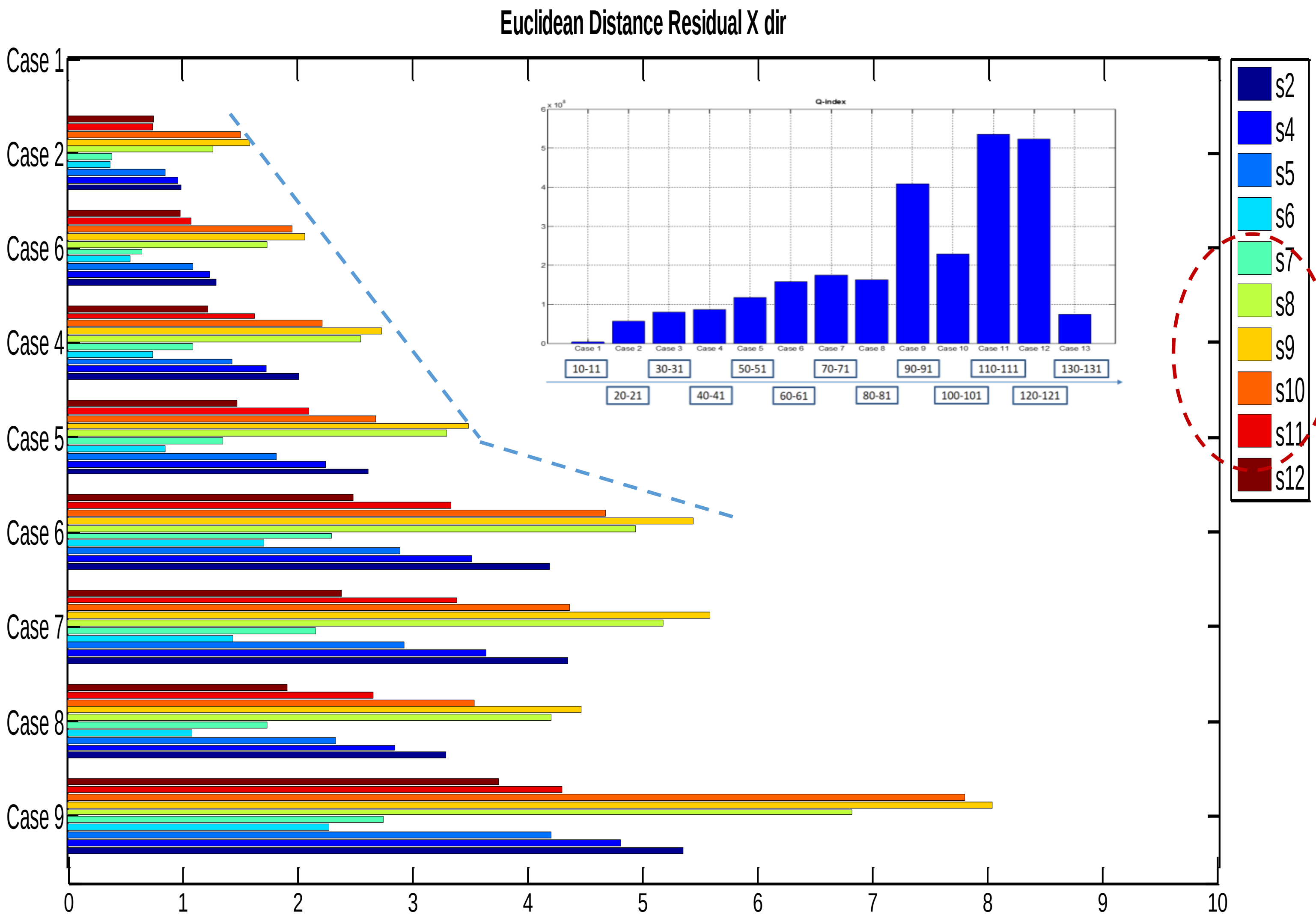
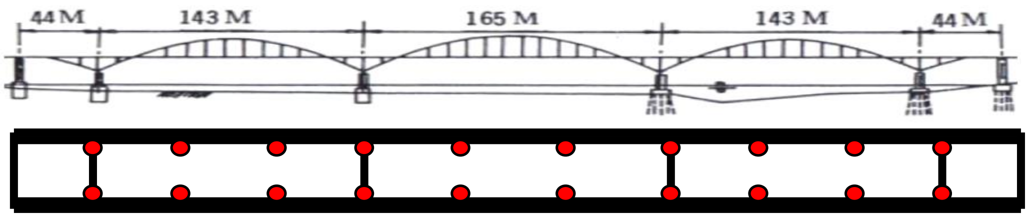
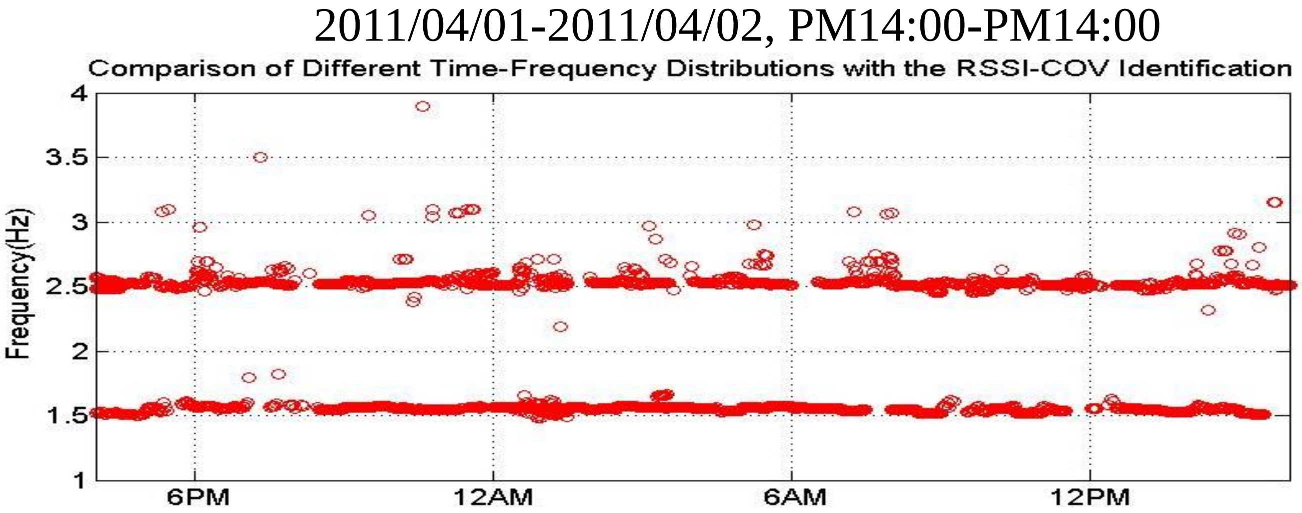
Damage detection & Localization : Sammon Map (scouring test)



Bridge Vibration Monitoring under Operating Condition

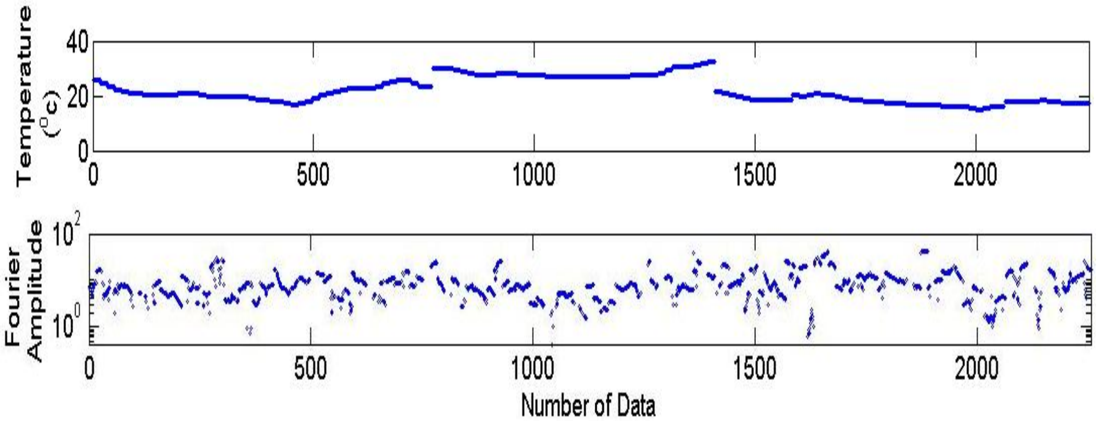
Environmental Effects for Vibration-based SHM



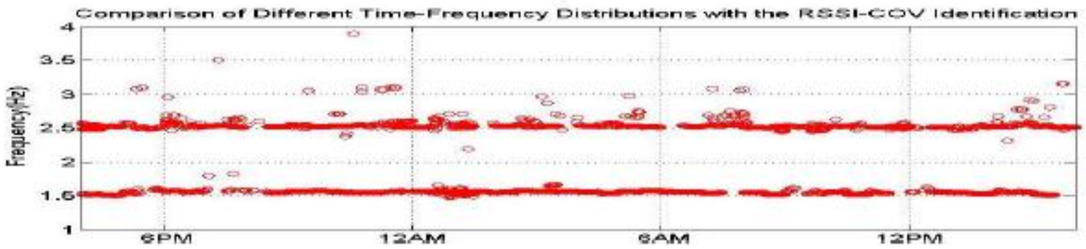


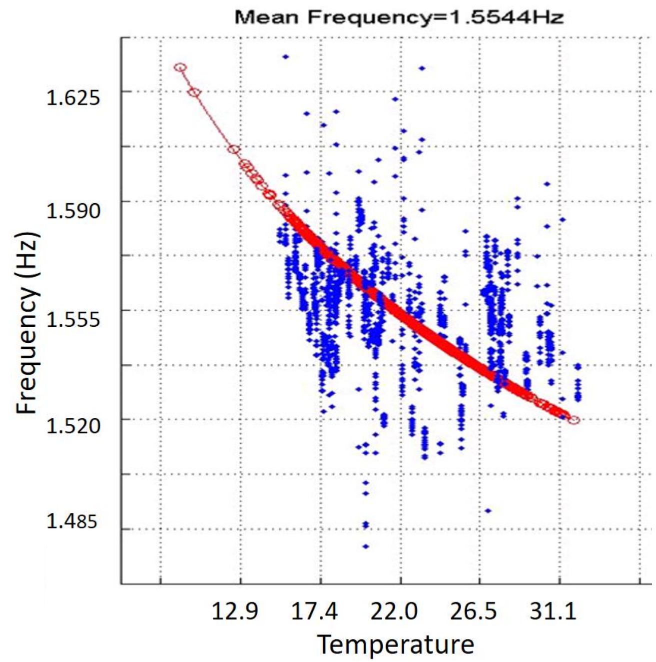
Using moving window SSI-VOV algorithm

Environmental Effect on Modal Parameter Identification

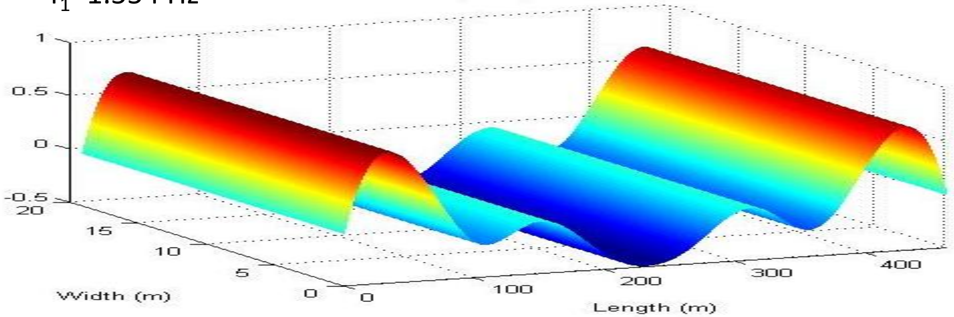


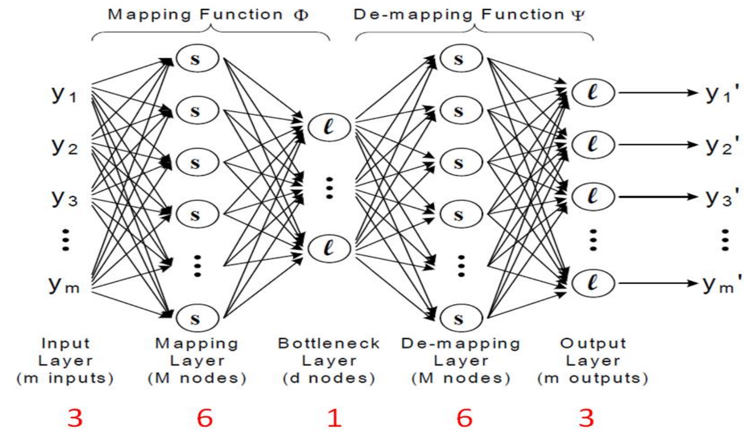
2011/04/01-2011/04/02, PM14:00-PM14:00





f_1=1.554 Hz





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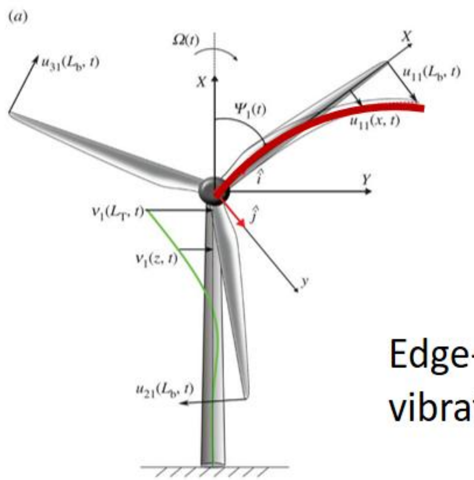
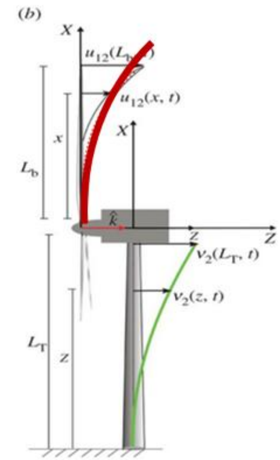
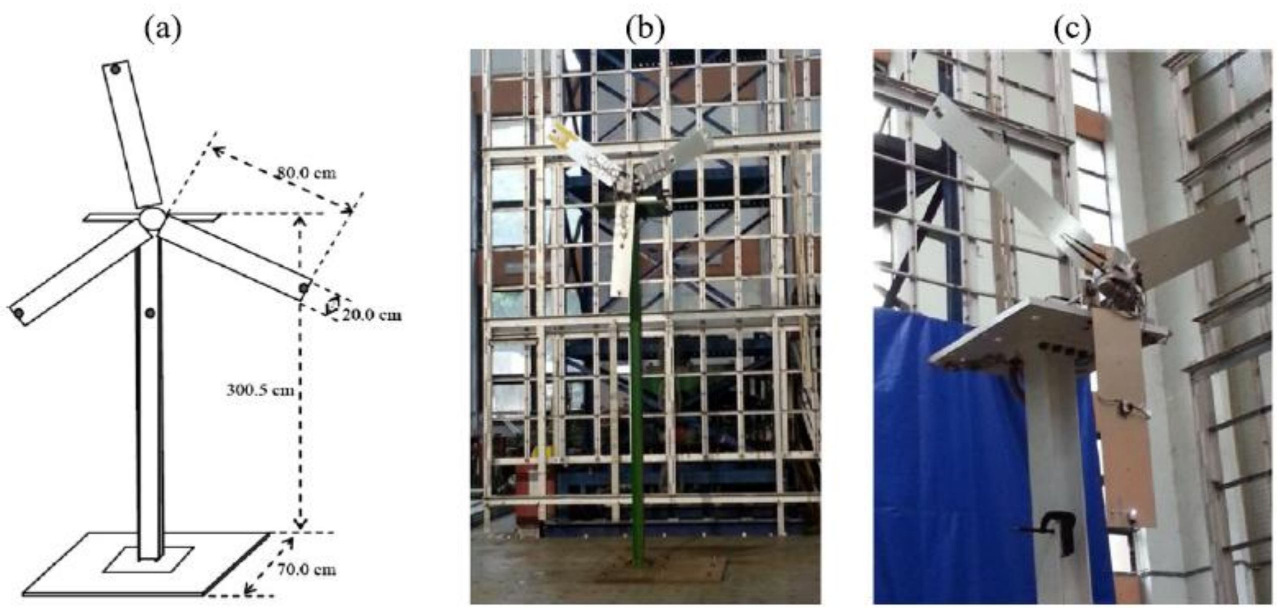
System identification of wind turbine blade under operating condition



Edge-wise vibration



Flap-wise vibration



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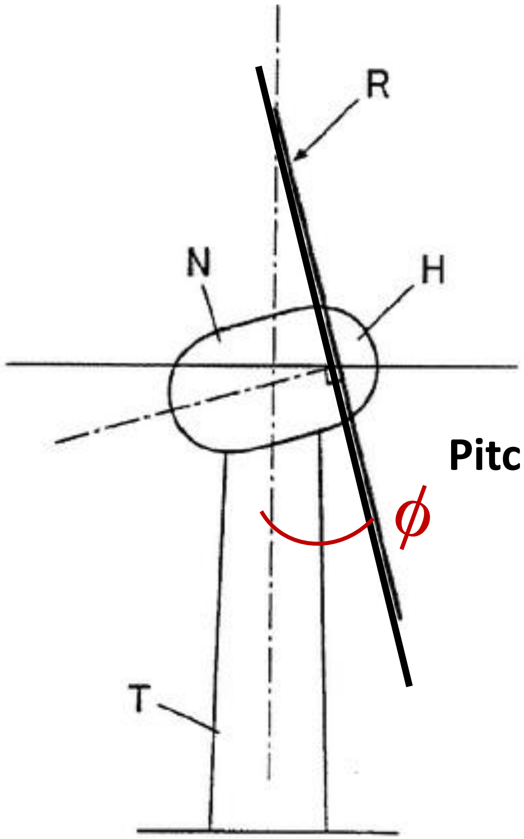
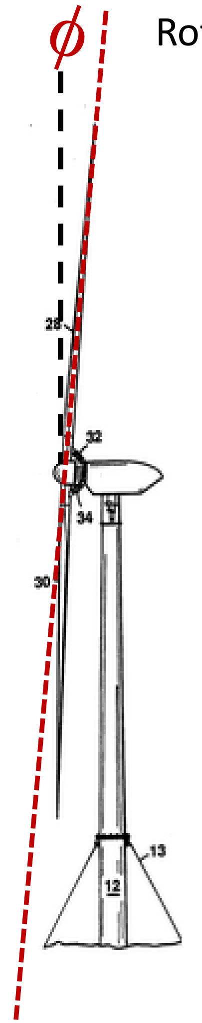
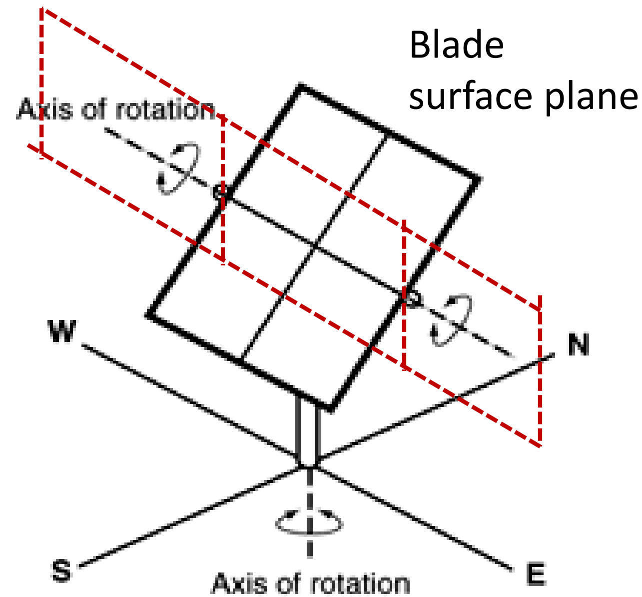
Geometry setup of turbine blade



Pitching angle

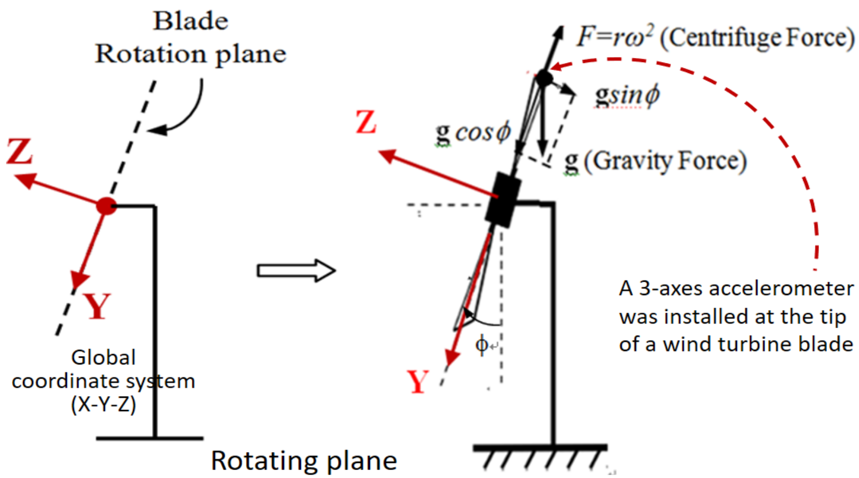


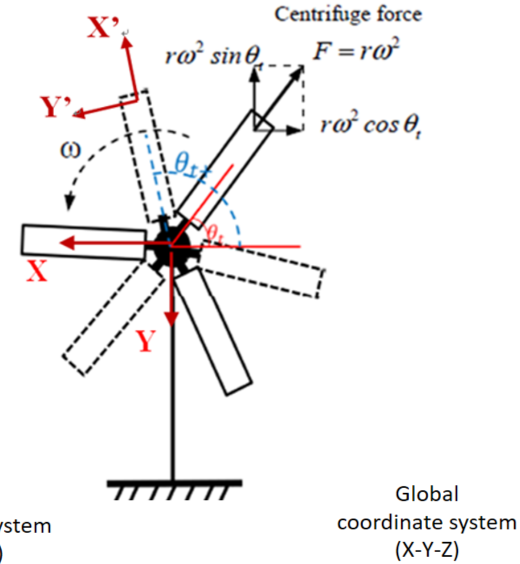
Change of tilting angle γ_2



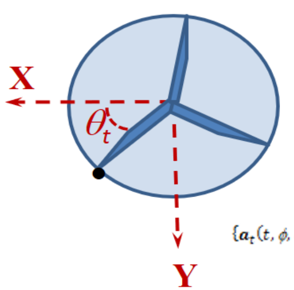
Change of rolling angle γ_1

Coordinate transformation between local and global coordinate system



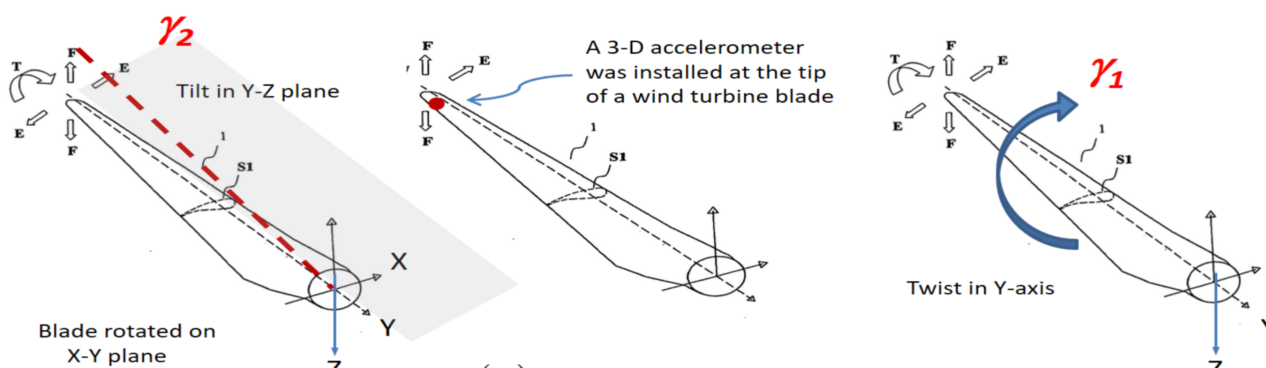


Rotating plane



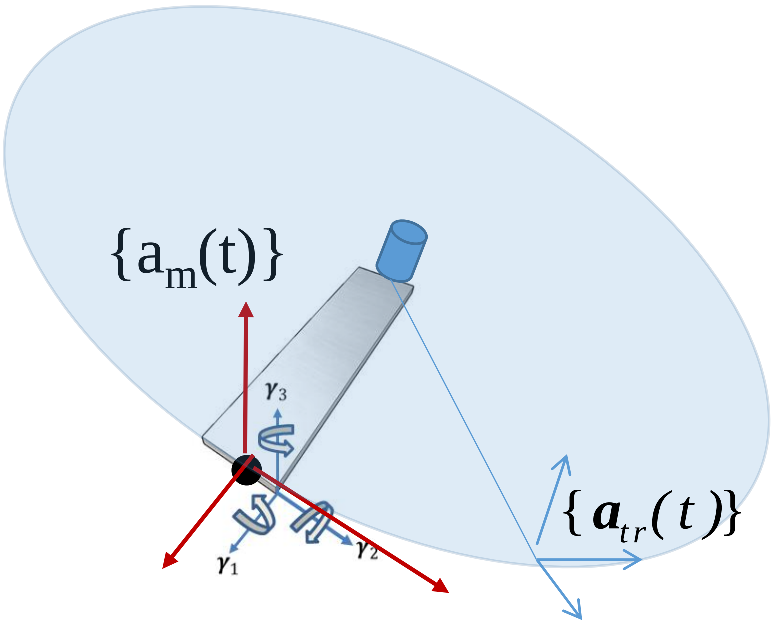
$$\{a_t(t,\phi,\theta_t)\} = \begin{bmatrix} a_{tx} \\ a_{ty} \\ a_{tz} \end{bmatrix} = \begin{bmatrix} -r\omega^2\cos\theta_t \\ -r\omega^2\sin\theta_t \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\phi & \cos\phi \\ 0 & \cos\phi & -\sin\phi \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\{a_{tr}(t,\phi,\theta_t)\} = \begin{bmatrix} -\cos\theta_t & -\sin\theta_t & 0 \\ \sin\theta_t & -\cos\theta_t & 0 \\ 0 & 0 & 1 \end{bmatrix} \{a_t(t,\phi,\theta_t)\}$$



$$a_m(\bar{\beta}) = \mathfrak{R}(-\gamma_{s1}, -\gamma_{s2}, -\gamma_{s3})\ \{a_{tr}(t)\}$$

Methodology of tracking blade geometry setup



$$\boldsymbol{a}_m(\bar{\boldsymbol{\beta}}) = \Re(-\gamma_{s1}, -\gamma_{s2}, -\gamma_{s3})\{\boldsymbol{a}_{tr}(t)\}$$

Sensor coordinate system (X''-Y''-Z'')

Local coordinate system (X'-Y'-Z')

$$\Re = \begin{bmatrix} \cos\theta + n_1^2(1-\cos\theta) & n_1 n_2(1-\cos\theta) - n_3\sin\theta & n_1 n_3(1-\cos\theta) + n_2\sin\theta \\ n_1 n_2(1-\cos\theta) + n_3\sin\theta & \cos\theta + n_2^2(1-\cos\theta) & n_2 n_3(1-\cos\theta) - n_1\sin\theta \\ n_3 n_1(1-\cos\theta) - n_3\sin\theta & n_3 n_2(1-\cos\theta) + n_1\sin\theta & \cos\theta + n_3^2(1-\cos\theta) \end{bmatrix}$$

$$\boldsymbol{a}_m(\bar{\boldsymbol{\beta}}) = \Re(-\gamma_{s1}, -\gamma_{s2}, -\gamma_{s3})\{\boldsymbol{a}_{tr}(t)\}$$

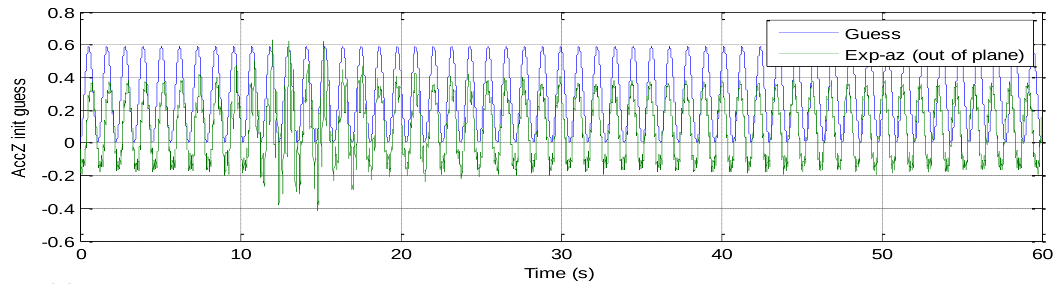
Measurement

Minimization of $J(\bar{\boldsymbol{\beta}}) = \left\| \boldsymbol{a}_e(t, \bar{\boldsymbol{\beta}}) - \boldsymbol{a}_m(t) \right\|$

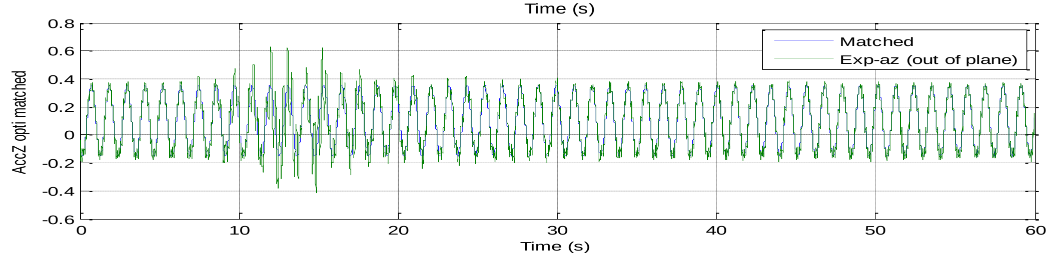
Determine $\bar{\boldsymbol{\beta}} = \langle \theta \quad \gamma_{s1} \quad \gamma_{s2} \quad \gamma_{s3} \quad \varphi \rangle$

Out-of-plane motion of turbine blade (test case of 50 rpm)

Recorded & initial assumption of flap-wise wave forms



Recorded and estimated flap-wise wave form



Residual signal of flap-wise wave form

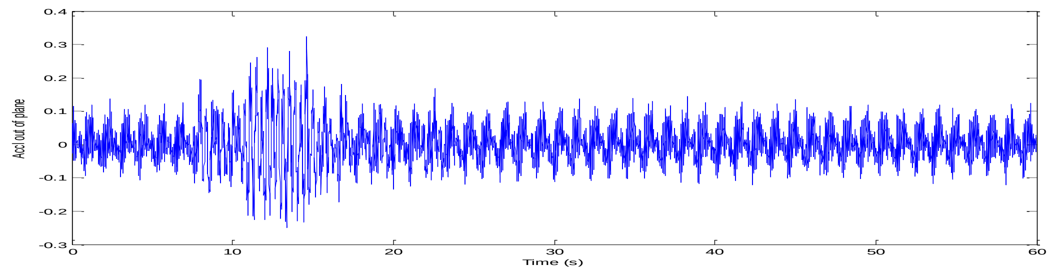
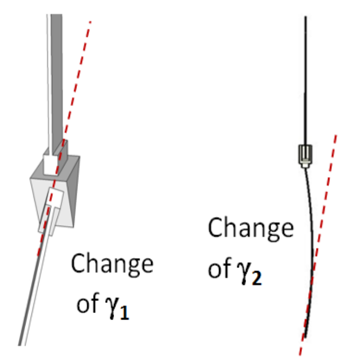


Table 1b: Identified wind turbine pitching and rolling angles from Test-2.

Test-2	ϕ	γ_1	γ_2	γ_3
15 rpm: Case 1	89.96 (90.0)	-6.58 (-5.0)	12.81 (10.0)	0.1 (0.0)
15 rpm: Case 2	90.18 (90.0)	-9.6 (-10.0)	12.05 (10.0)	0.63 (0.0)
15 rpm: Case 3	85.1 (90.0)	85.1 (90.0)	10.69 (10.0)	-0.84 (0.0)

Note: (*) indicate the blade rolling angle in its original setup.



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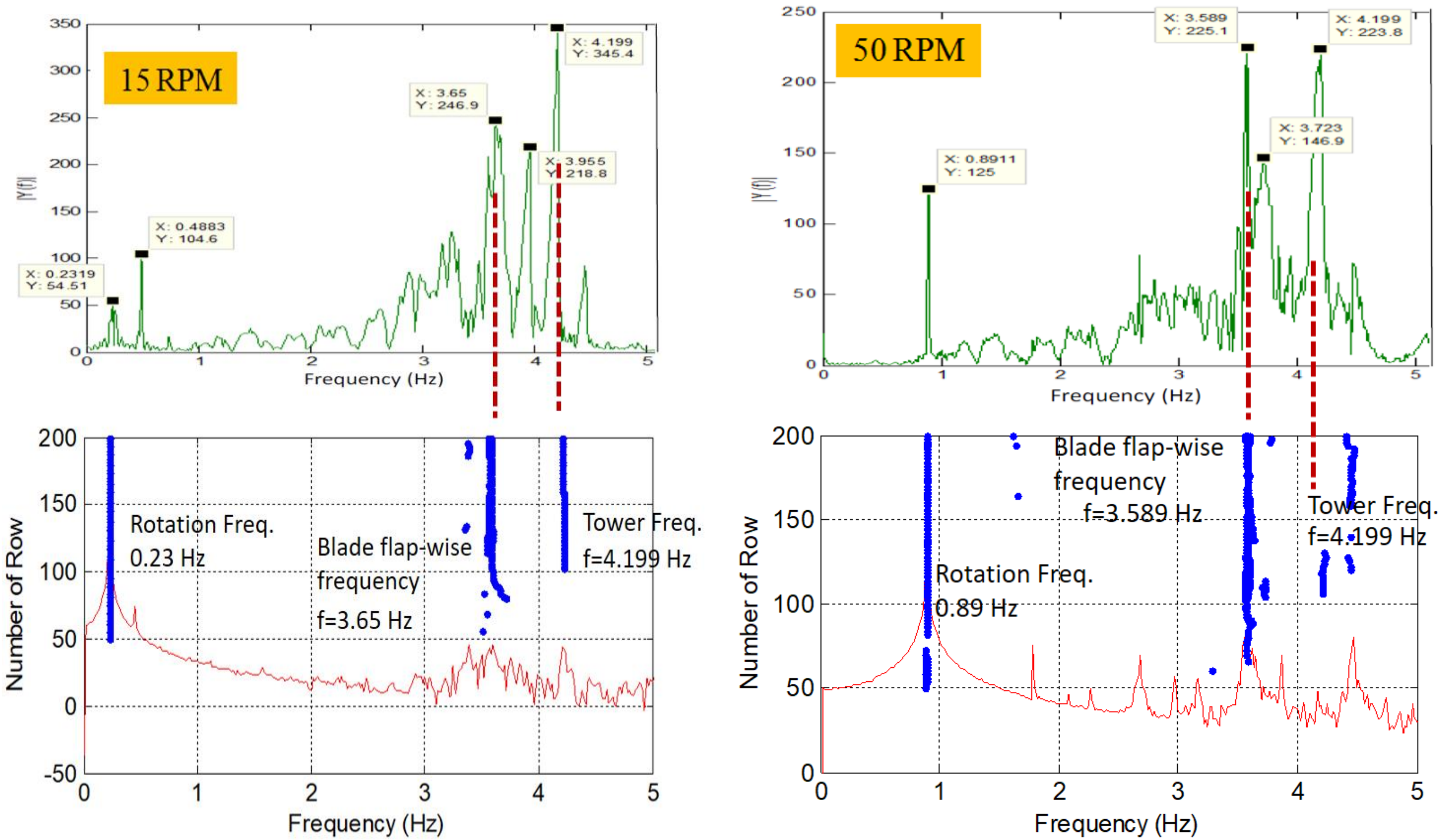
Results of Identification (1)



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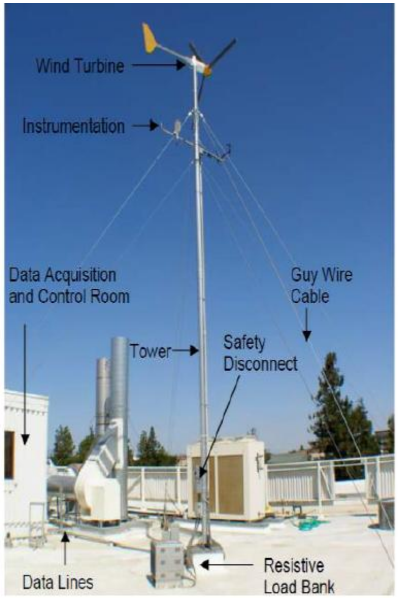
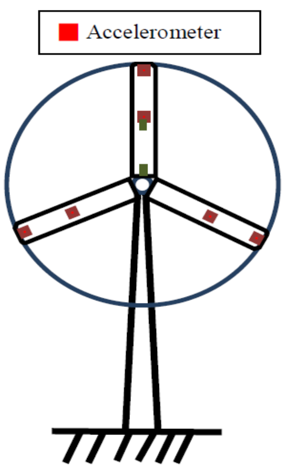
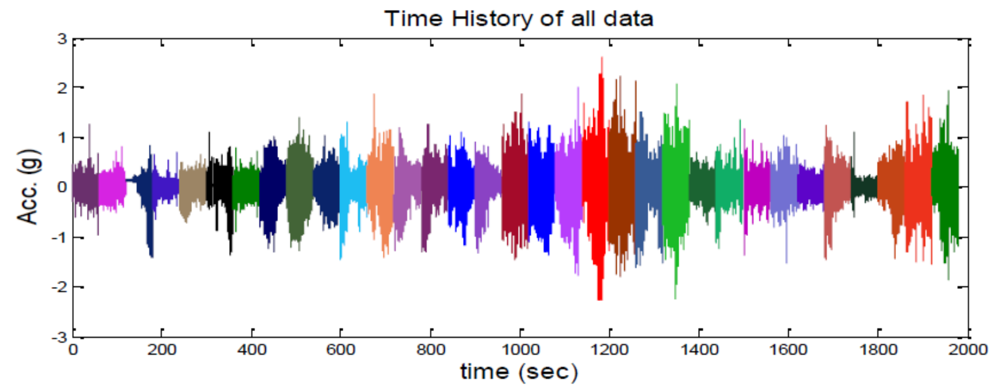
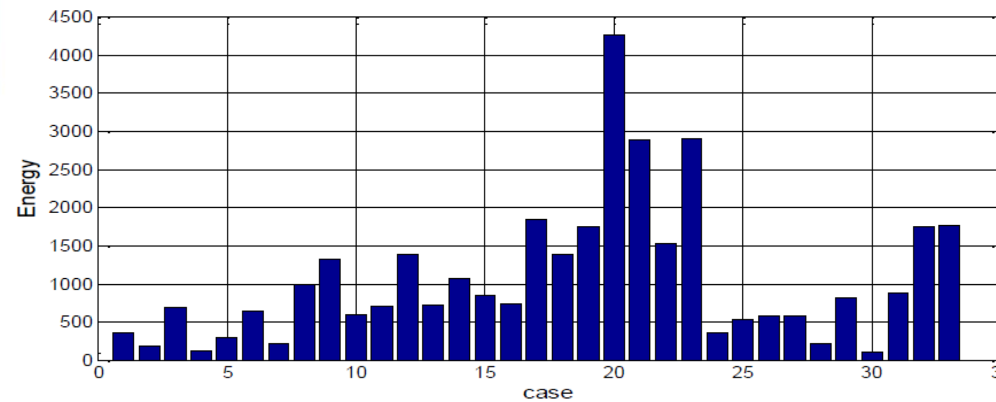
Field Experimental Study

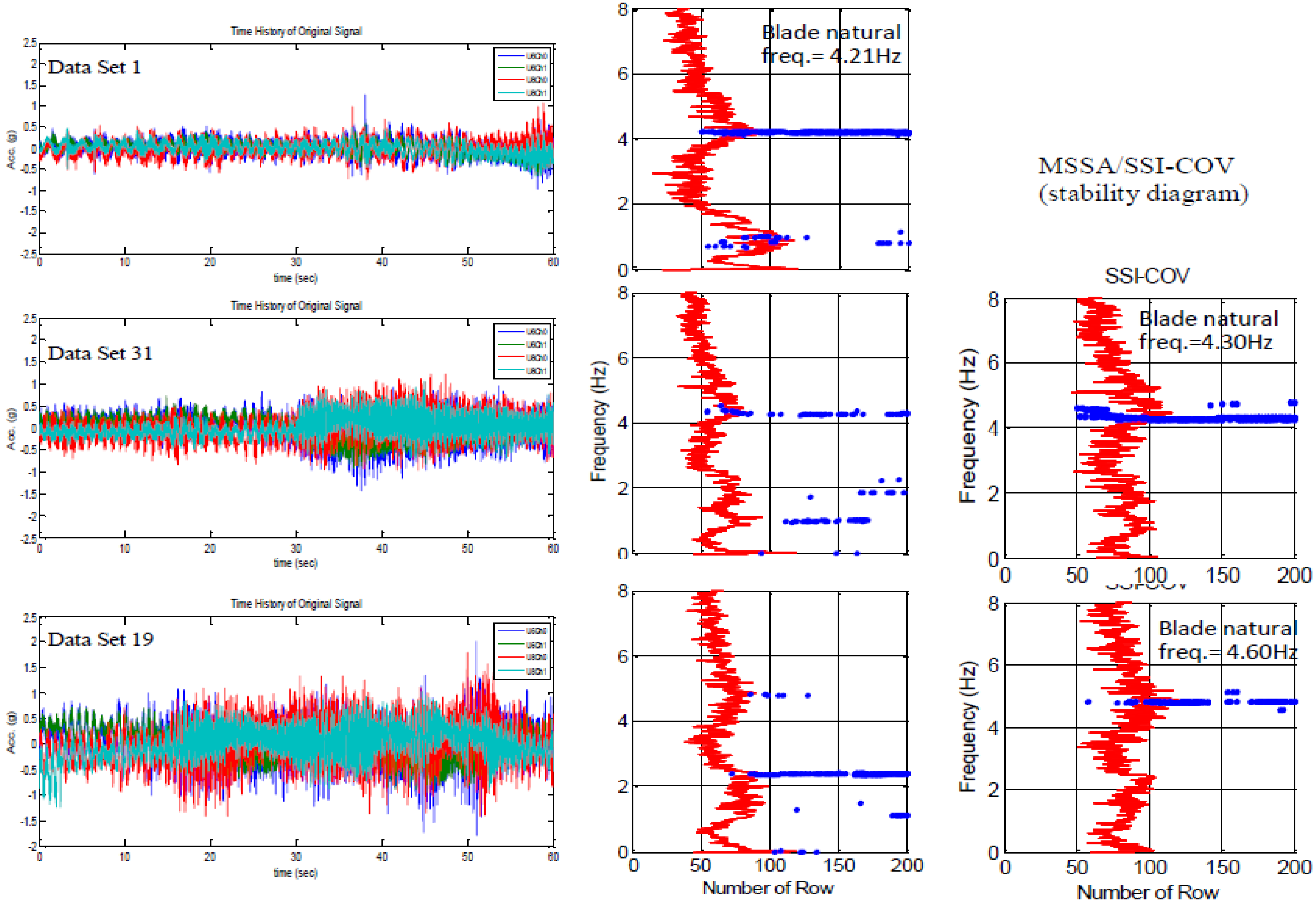








Field Experimental Study



(a) Recorded acceleration of out-of-plane motion of blade from three different datasets (b) Plot the stability diagram (from SSI-COV) from each dataset, (c) Plot the stability diagram (using MSSA to remove the rotation frequency signal) for dataset 31 and 19.

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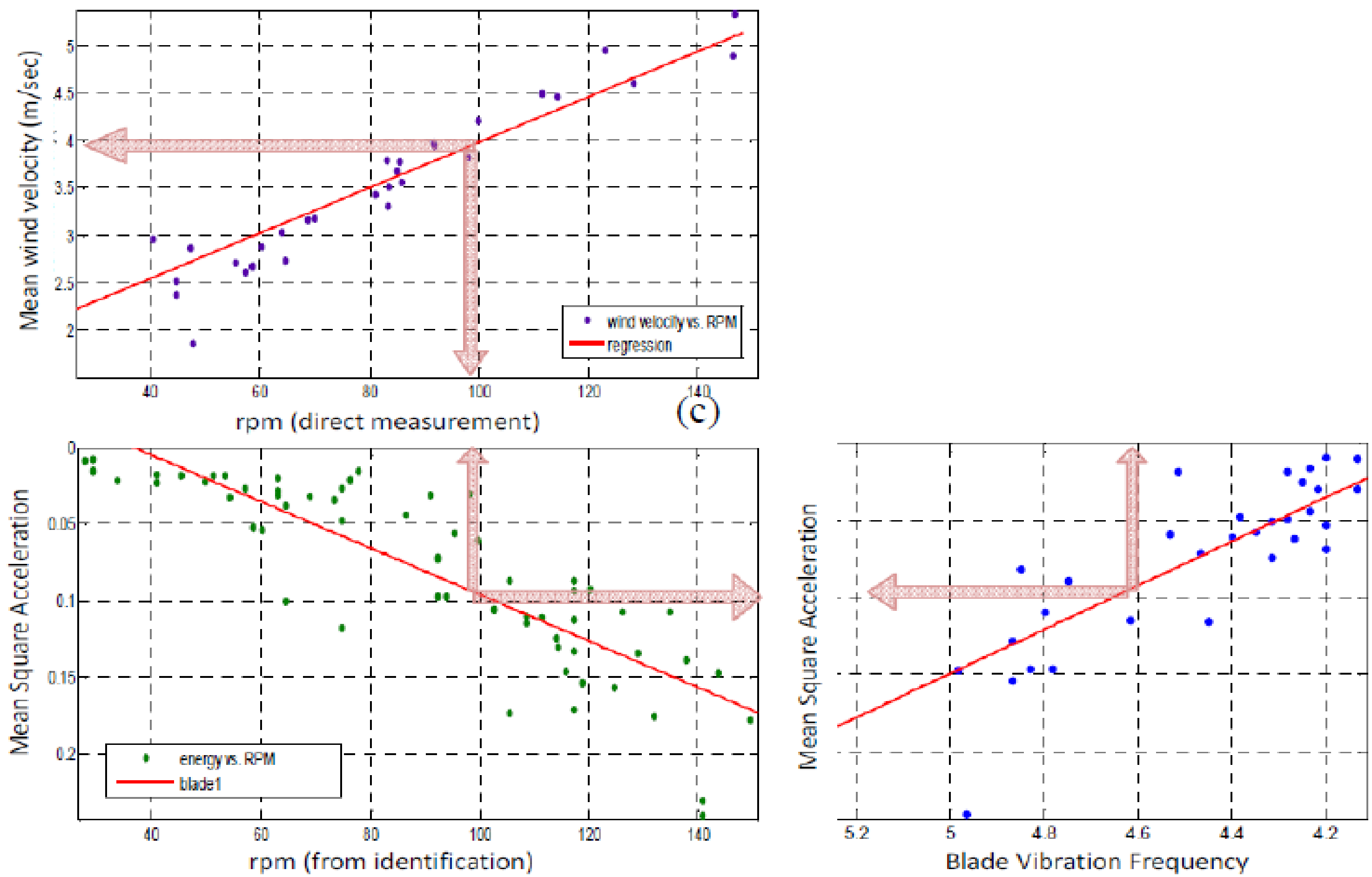
Field Experimental Study

(a)

(b)



(a) The relationship between the mean wind velocity, the turbine rotation Frequency and the identified blade vibration frequency.

Conclusions

Centralized Data Analysis Techniques

System Identification :
- Stochastic Subspace Identification (**ambient data**)
- Recursive Subspace Identification (**earthquake response**)

Damage Assessment Level-3 :
- LSSM+EMCM (stiffness reduction---earthquake response)

Damage Detection & Localization (Level-1 & Level-2):
- Null-space damage index
- Sammon map--- 2D visualization

Almost Real-time Damage Assessment

Sensor-Level Data Analysis Techniques

Damage Detection & Localization (Level-1 & Level-2):
- Wavelet-based correlation analysis

Challenges in SHM of Civil Structures

Civil Infrastructures

- Huge size (large scale) and vast mass of materials,
- Long service life (> 50 years),
- Harsh and varying environmental conditions
- In-place conditions different from the design assumptions

OMA based damage assessment

√ Develop measurement strategies,
√ Increase the number of excited modes,
√ Eliminate environmental influences,
√ Increase the sensitivity to local damages,

Damage detection (alarm level)

√ Explore more damage related dynamic features,
√ Consider statistically relevant deviation,
√ For permanent monitoring '**automatic system identification**' is mandatory,
√ Highly advisable for periodic monitoring,
√ Develop modal updating technologies (Optimization algorithm)

2017	Jun-Da Chen & **Chin-Hsiung Loh**, "Tracking Modal Parameters of Building Structures from Experimental Studies and Earthquake Response Measurements," *Published in Int. J. of Structural Health Monitoring, March 2017 DOI: 10.1177/ 1475921717696339.*
2017	**Chin-Hsiung Loh** & Jun-Da Chen, "Tracking Modal Parameters from Building Seismic Response Data Using Recursive Subspace Identification Algorithm," *Published in Int. J. Earthquake Engineering & Structural Dynamics, April 2017, DOI: 10.1002/eqe.2900*
2016	**Chin-Hsiung Loh***, Chuan-Kai Chan, Sheng-Fu Chen, Shieh-Kung Huang, "Vibration-based Damage Assessment of Steel Structure Using Global and Local Response Measurements," *Earthquake engineering & Structural dynamics*, 2016; 45:699-718.
2015	**Chin-Hsiung Loh***, Yu-Ting Huang, Wan-Ying Hsiung, Yuan-Sen Yang, Kenneth J. Loh, "Vibration-Based Identification of Rotating Blades Using Rodrigues' Rotation Formula from A 3-D Measurement," Journal of Wind and Structures, Vol.21, No.6, December 2015, pp.677-691.
2015	Chin-Hsiung Loh*, Shu-Hsien Chao, Jian-Huang Weng, Tzu-Hsiu Wu, "Application of Subspace Identification Technique to Long-Term Seismic Response Monitoring of Structure," *Earthquake Engineering & Structural Dynamics, (2015), 44:385-402*
2015	**Chin-Hsiung Loh,** T Y Hung, S F Chen and W T Hsu, "Damage Detection in Bridge Structure Using Vibration Data under Random Travelling Vehicle Loads," *Journal of Physics: Conference Series* (DAMAS) 628 (2015) 012044.
2014	Chao, S.H., and **Loh, Chin-Hsiung**, "Vibration-based damage identification of reinforced concrete member using optical sensor array data," *J. Structural Health Monitoring*, Vol.12, No. 5-6, 397-410. 2014. IF=3.193
2014	Chao, S.H., **Chin-Hsiung Loh**, Tseng, M.H., "Structural Damage Assessment Using Output-Only Measurement: Localization and Quantification," *Int. Journal of Intelligent Material Systems and Structures*, Vol. 25(9) 1097–1106, 2014. (IF=0.45)
2014	**Loh, Chin-Hsiung.** "Sensing solutions for assessing and monitoring of dams," Chapter 10, Sensor Technologies for Civil Infrastructures (Vol.2: Applications in Structural Health Monitoring), Edited by M.L. Wang, J.P. Lynch and H. Sohn, Elsevier Ltd 2014, pp: 275~308. (Book Chapter Contribution) (IF=0.45)
2013	Chao, S.H., **Loh, C.H.**, Tseng, M.H., "Structural Damage Assessment Using Output-Only Measurement: Localization and Quantification," Accept for publication in Int. Journal of Intelligent Material Systems and Structures, Jume 2013. IF:1.523
2013	Chao, S. H. and Loh, C. H., "Application of Singular Spectrum Analysis to Structural Monitoring and Damage Diagnosis of Bridges," *J. of Structures and Infrastructural Systems* 2) Volume 10, 2014 - Issue 6 708-727
2013	**Loh, C.H.** and Liu, Y.C., "Application of recursive SSA as data pre-processing filter for stochastic subspace identification," Accept for publication in Smart Structures and Systems, Vol.11, No.1 (2013) IF:1.430

Acknowledgements

科技部專題研究案

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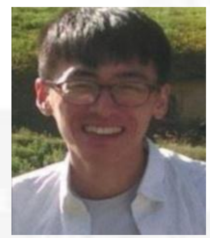
2015-8/2016-7: MOST 104-2625-M-002-016; MOST 104-2221-E-002-013
2014-8/2015-7: MOST103-2625-M -002-006; MOST 103-2221-E-002-064

Research Assistant from Prof. Loh's research Lab


林佳樺


薛 汶


陳俊達


涂雅靜


李宗憲


許維庭


黃昱廷


熊婉贏


葉乃睿

Than you for your listening !

Questions ?

臺灣大學

National Taiwan University