# 智慧型結構技術研發 –

# 應用子空間系統識別法於結構安全性評估
# 及
# 應用線上小波轉換進行結構控制

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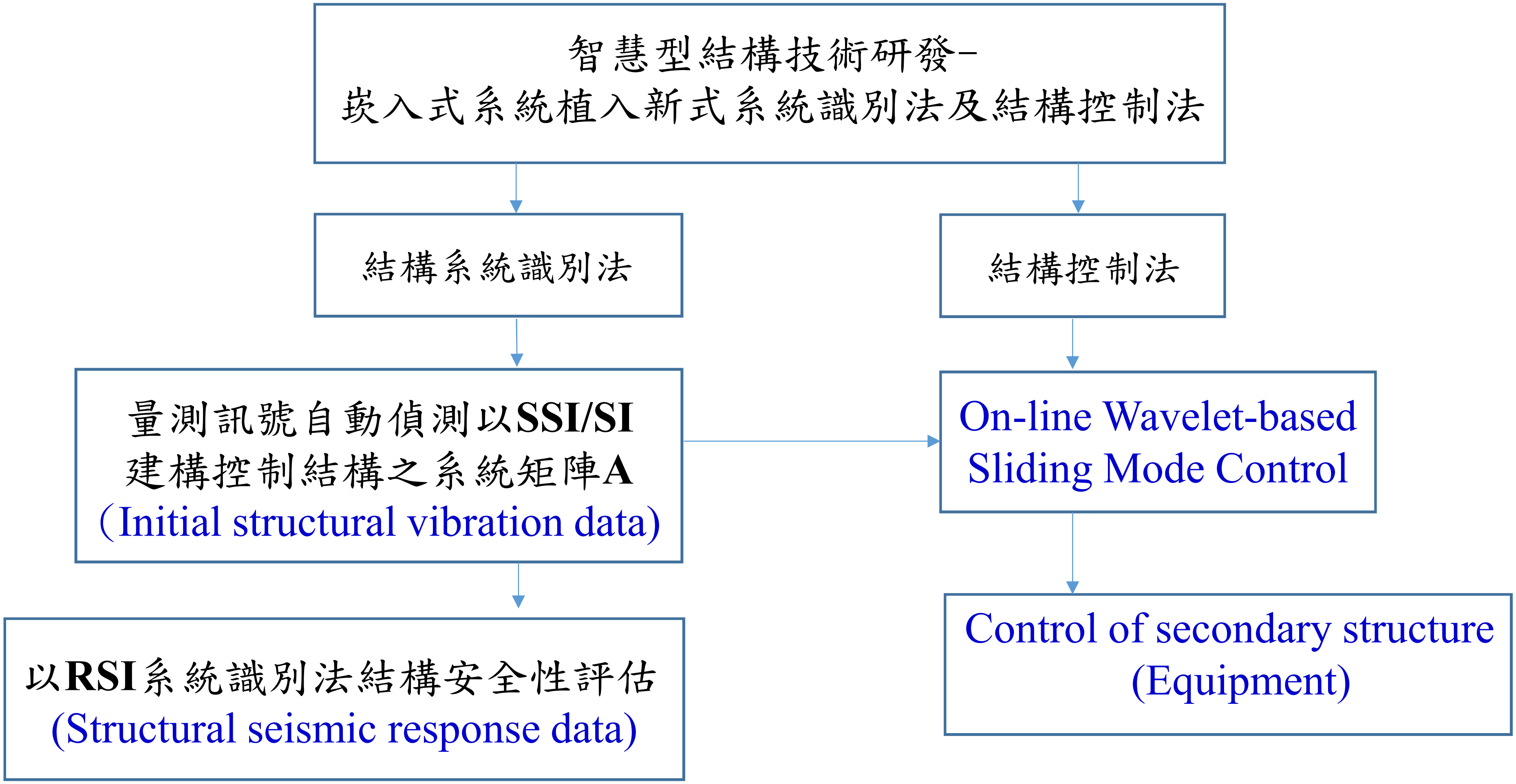
## 研究架構



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# 以RSI系統識別法結構安全性評估

1. **On-line System Identification & Damage Detection under Earthquake Excitation**

**Automatic SI/RSI on structural seismic response measurement**

**RSI**
Fixed/Enlarged-length moving window

2. **Modal Parameters :** Frequency / Damping Ratio / Mode Shape

**Damage Detection**
LSSM / EMCM
**(1) Build up reference model**
**(2) Recursively update model**

3. **Theoretical Verification:**

- **Experimental Study: Shaking Table Tests**
- **Practical Applications: Structural Seismic Response Data**

**Seismic Damage :**
Localization
Quantification
Occurrence of Time


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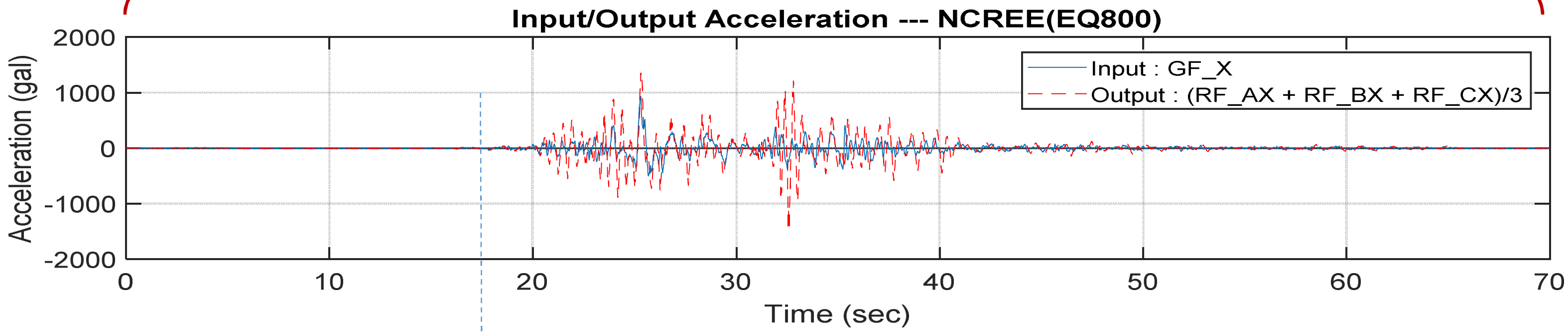
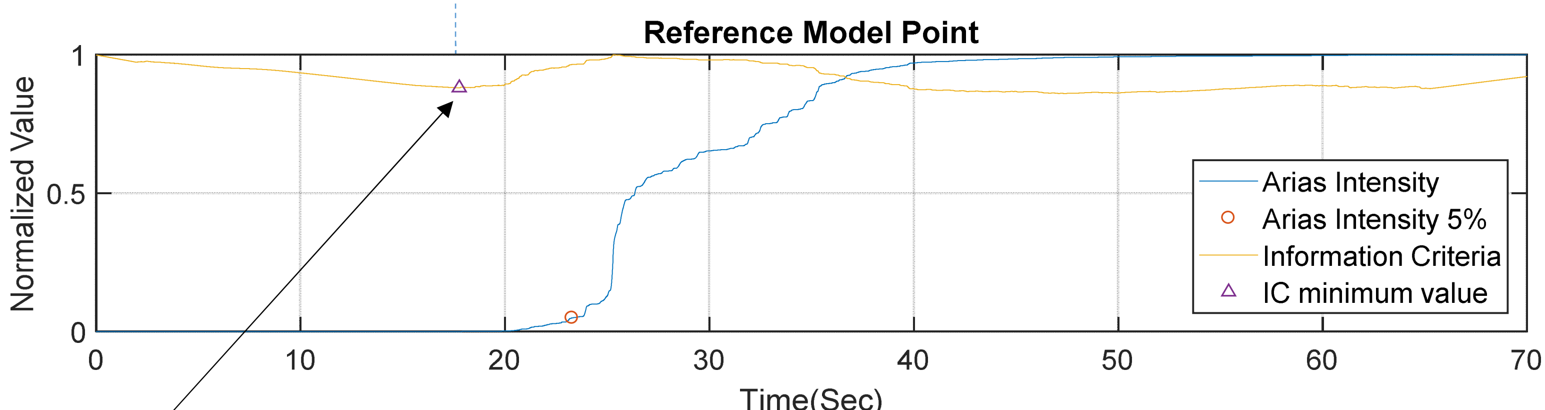
# IC Dominant-wave Arrival Detection

**Recorded data length**




Use significant wave arrival indicator $IC(k) = k \cdot \log\{var(x[1,k])\} + (N-k-1) \cdot \log\{var(x[k+1,N])\}$

Identify the instant of time in between Si and RSI




Breaking point for SI/RSI



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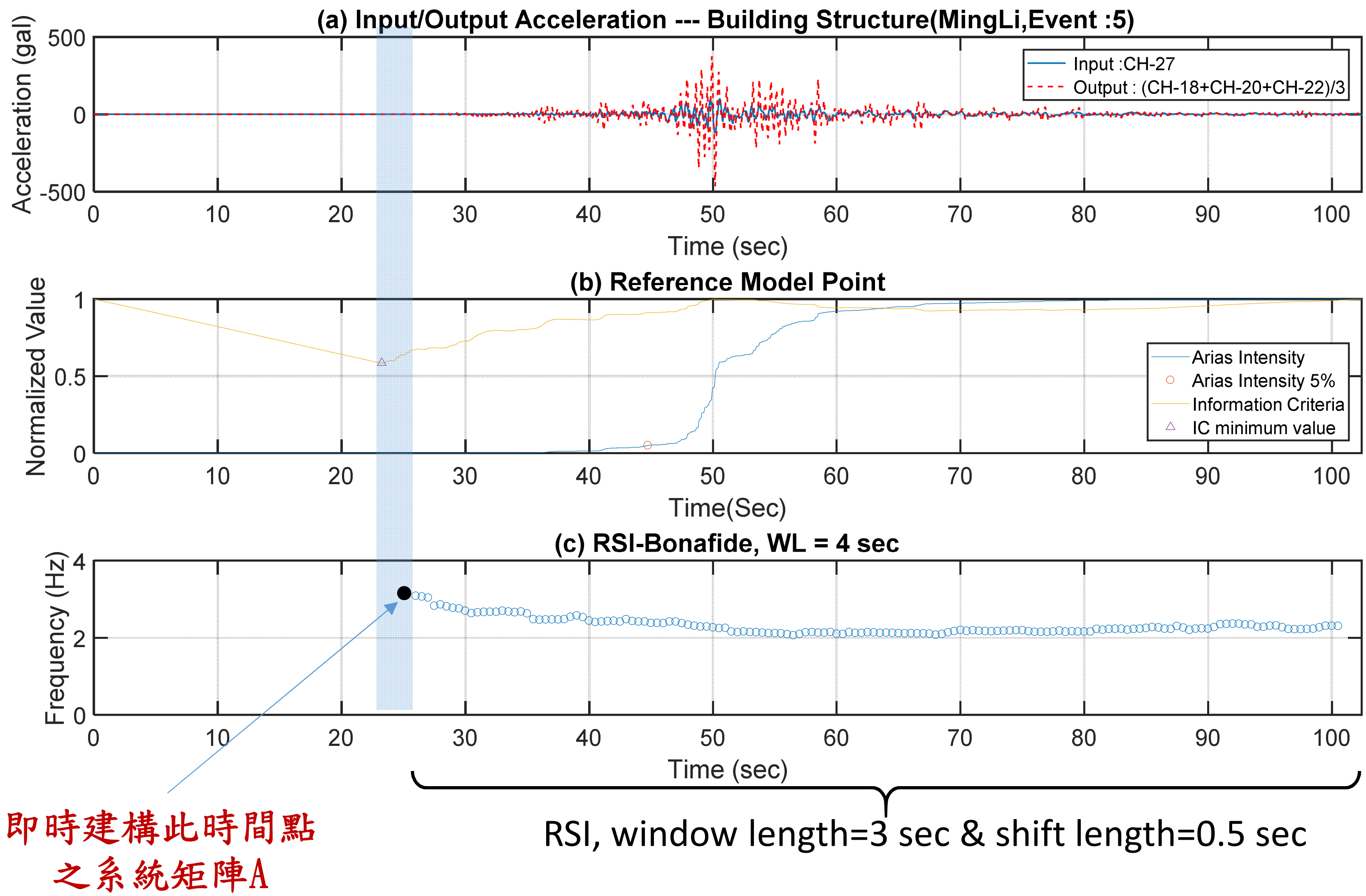
# Analysis of Ming-Li Elementary School Building



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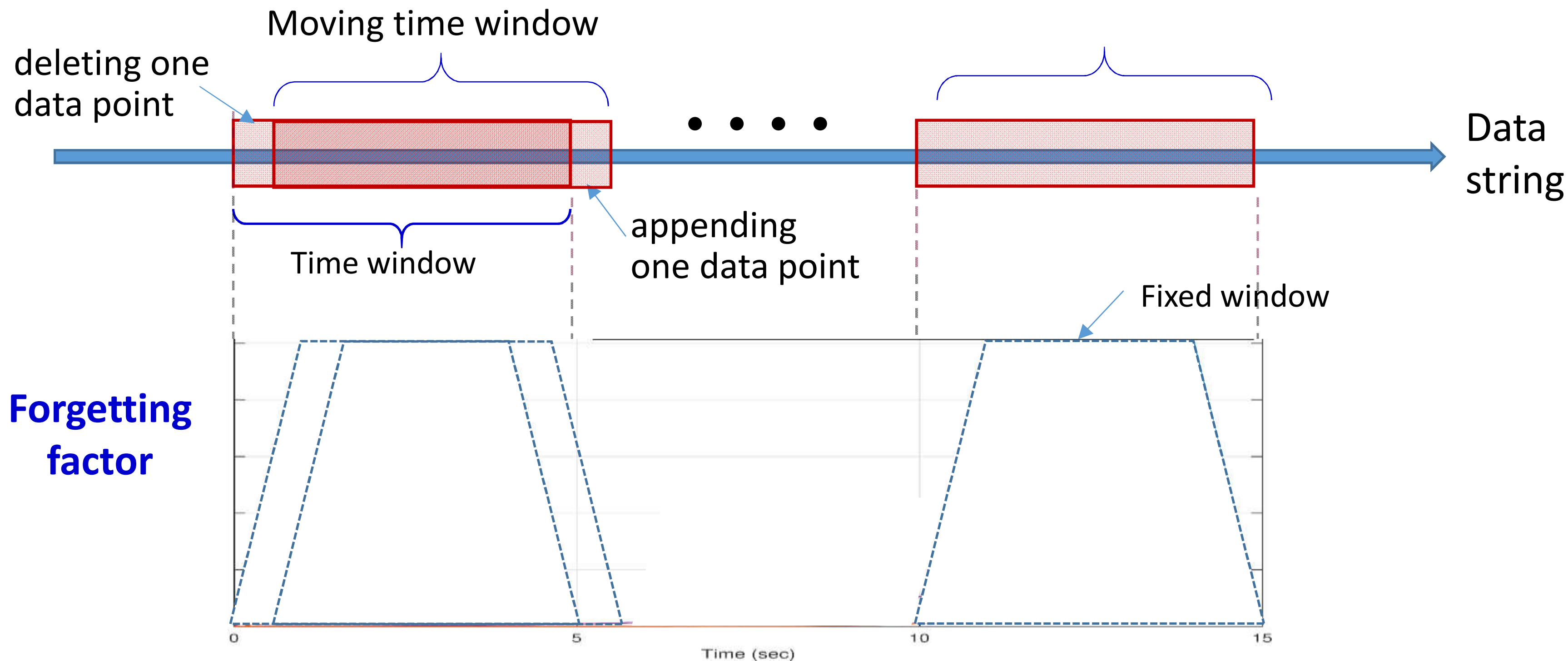
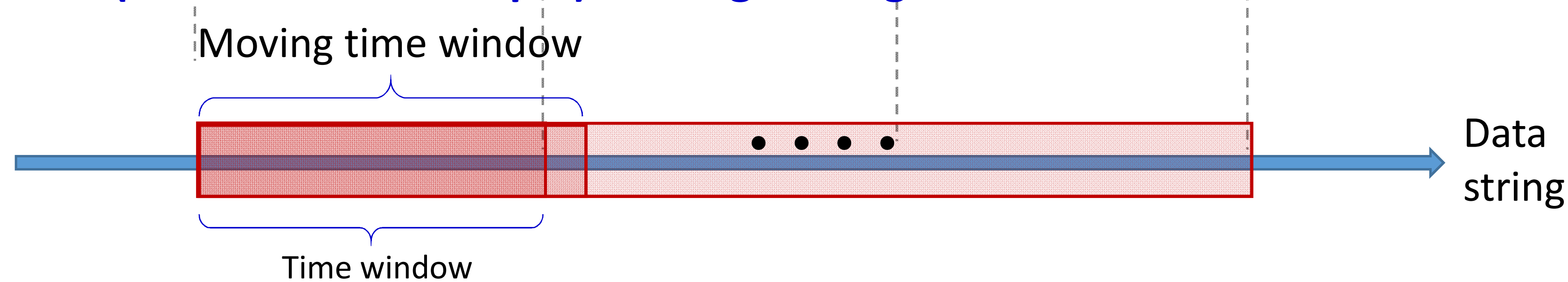
# Recursive Identification (with/without forgetting factor)

## Method 1 (BonaFide RSI): Fixed-length window




## Method 2 (RSI Inversion-Oblique) : Enlarged-length window



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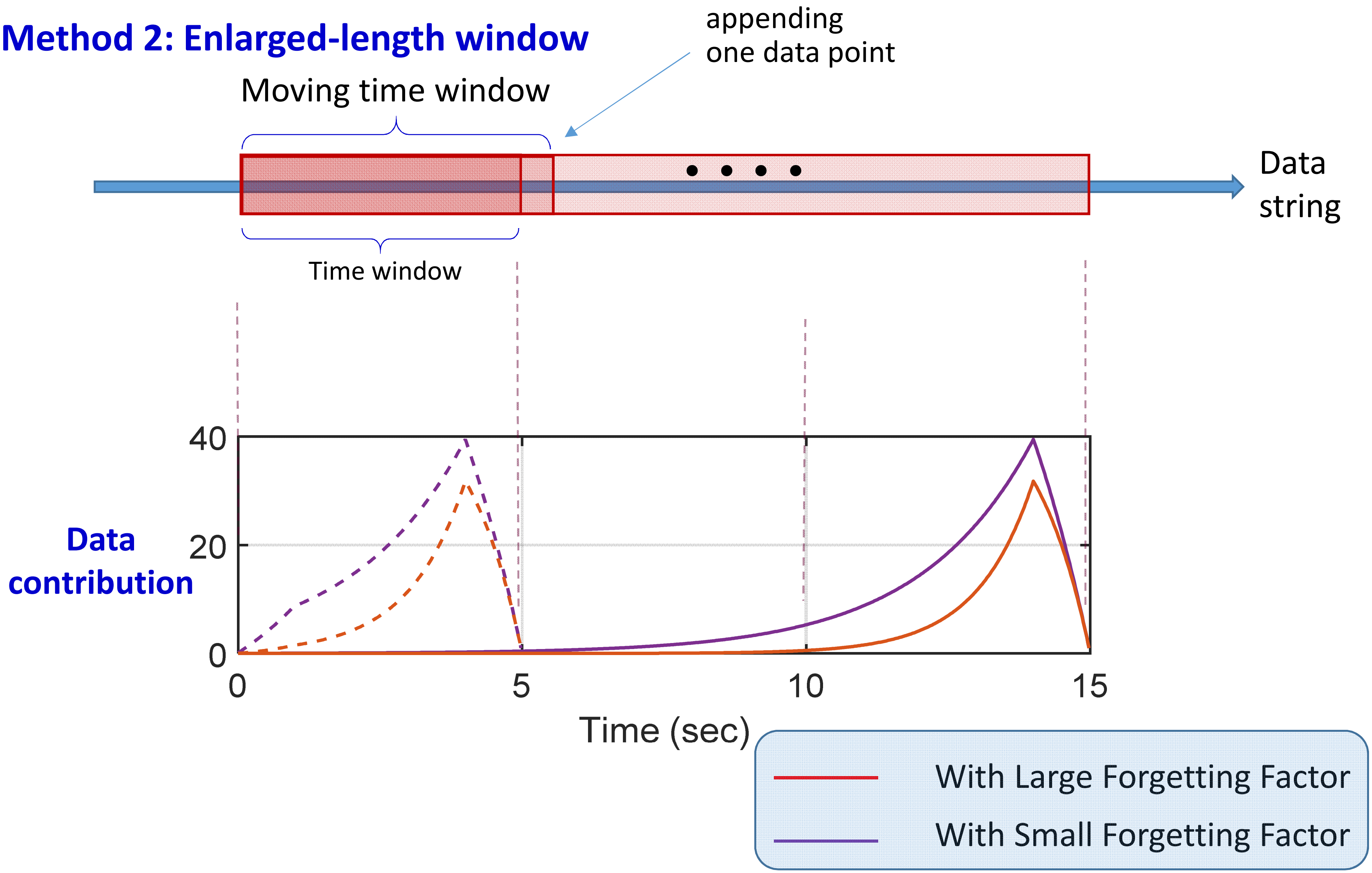
# Recursive Identification (with forgetting factor)

## Method 2: Enlarged-length window



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# Methodologies on Damage Assessment

Frequency / Mode Shape at each time instant is obtained from RSI-methods…

Two Step Damage Detection Algorithm

- **Least Squares Stiffness Method** (LSSM)

- Model Updating technique:
  **Efficient Model Correction Method** (EMCM)



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# Least Squares Stiffness Method (LSSM)

- Once modal frequencies and mode shapes are identified by RSI-Inversion Oblique, and information of mass is properly assumed…

Least-squares Member stiffness

$$\mathbf{K}\phi_j=\lambda_j\mathbf{M}\phi_j$$

$$\begin{bmatrix}\Delta_1\\ \Delta_2\\ \vdots\\ \Delta_n\end{bmatrix}\begin{bmatrix}k_1\\ k_2\\ \vdots\\ k_n\end{bmatrix}=\Delta k=\Lambda=\begin{bmatrix}\Lambda_1\\ \Lambda_2\\ \vdots\\ \Lambda_n\end{bmatrix}$$

id id

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

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

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

$$\Delta_j=\begin{bmatrix}\phi_{1,j} & \phi_{1,j}-\phi_{2,j} & 0 & & \cdots & 0\\ 0 & \phi_{2,j}-\phi_{1,j} & \phi_{2,j}-\phi_{3,j} & & \cdots & 0\\ \vdots & \vdots & & \ddots & \vdots & \vdots\\ 0 & 0 & \cdots & & \phi_{n-1,j}-\phi_{n-2,j} & \phi_{n-1,j}-\phi_{n,j}\\ 0 & 0 & \cdots & & 0 & \phi_{n,j}-\phi_{n-1,j}\end{bmatrix}$$

$$\Lambda_j=\begin{bmatrix}\phi_{1,j}\lambda_j m_1\\ \phi_{2,j}\lambda_j m_2\\ \vdots\\ \phi_{n,j}\lambda_j m_n\end{bmatrix}$$

**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.

# Efficient Model Correction Method (EMCM)

➢ Input:
(1) Nominal Mass & Stiffness Matrix
(2) Modal Frequencies & Mode Shapes

**Efficient Model Correction Method (EMCM)**

➢ 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]

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

**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**

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

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



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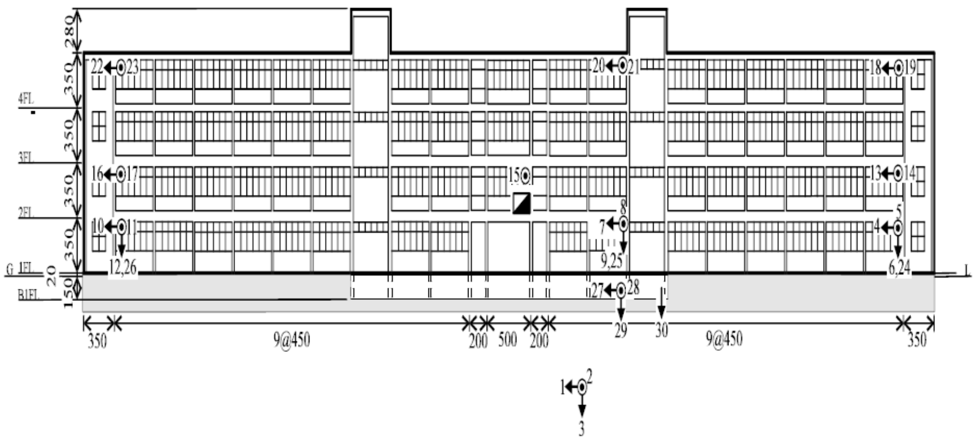
# Ming-Li elementary school
# (Through two stages of retrofitting)



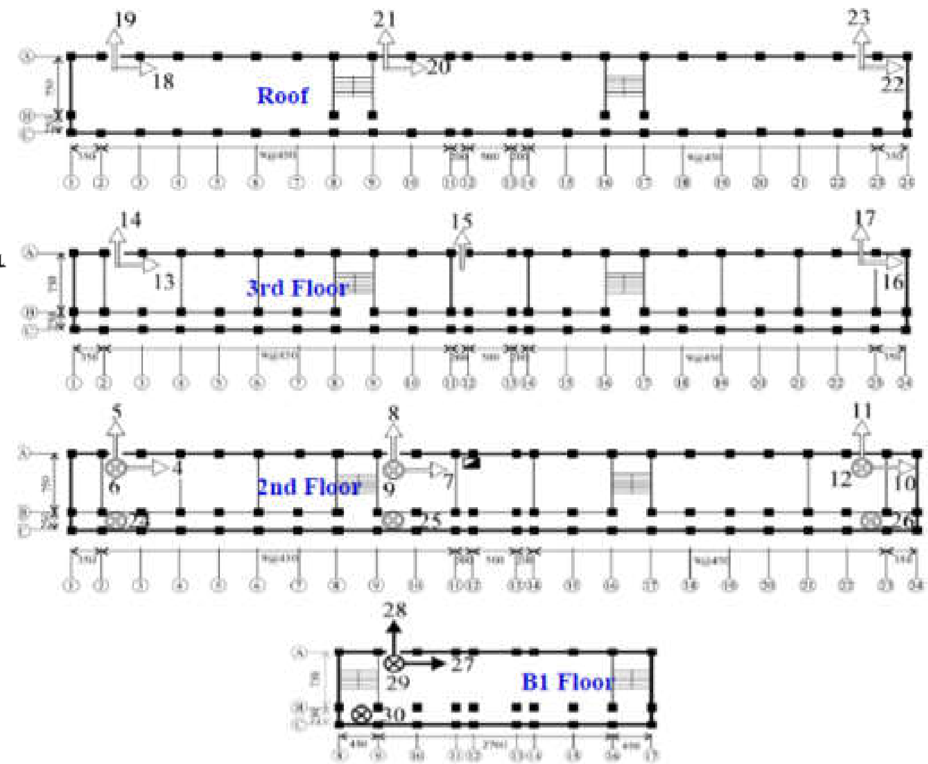



Photo courtesy of Google map.



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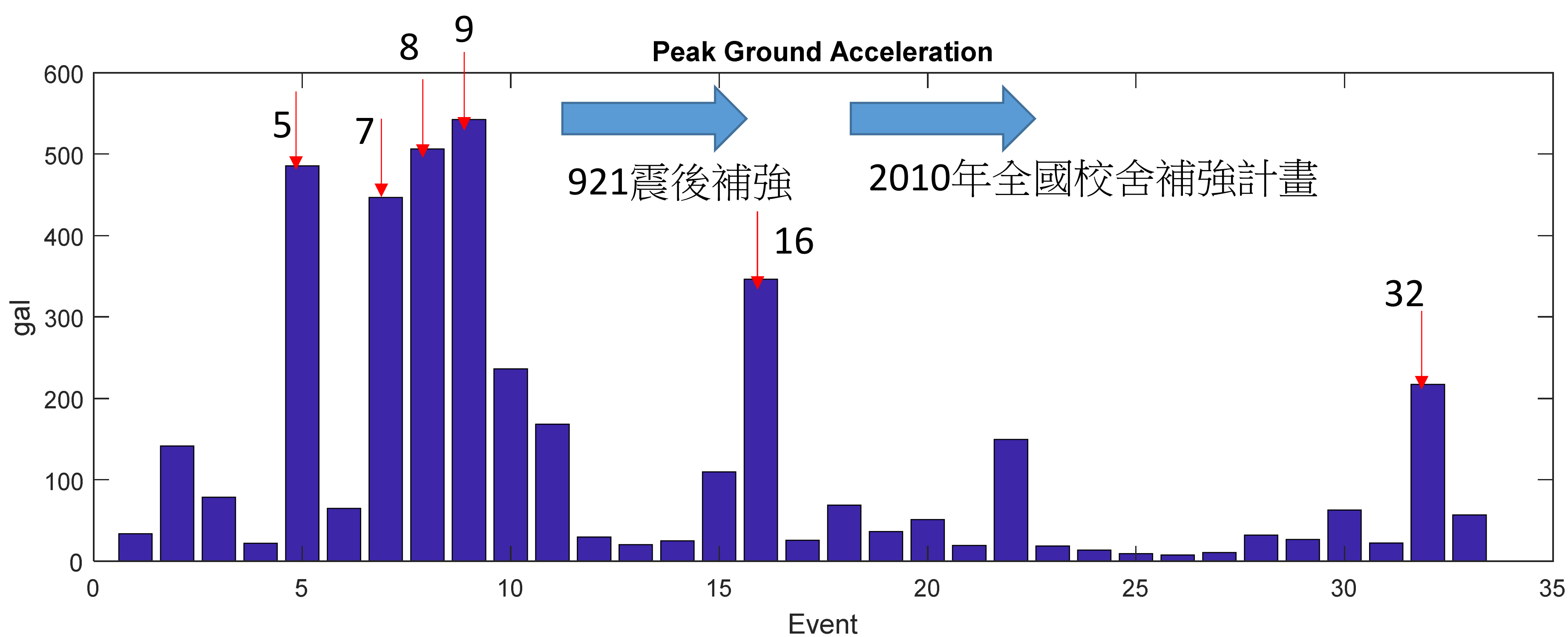
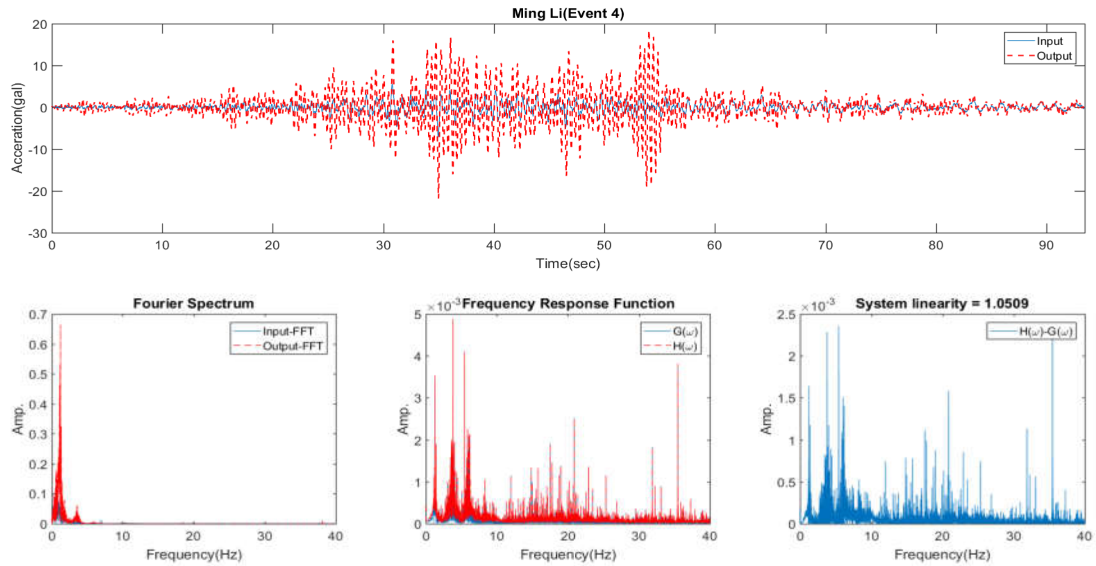
# Description of the recorded event



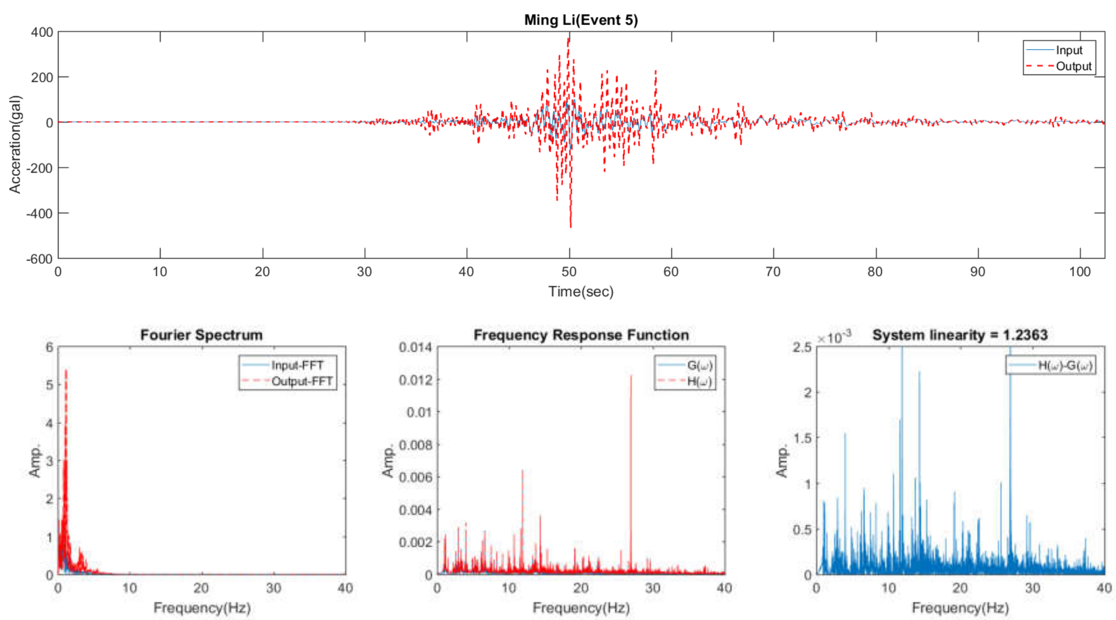

| Event | 5 | 7 | 8 | 9 | 16 | 32 |
| --- | --- | --- | --- | --- | --- | --- |
| Data | 1999/09/20 | 1999/09/22 | 1999/09/25 | 1999/11/01 | 2009/12/19 | 2010/11/21 |
| PGA(gal) | 485.8 | 446.9 | 506.6 | 542.6 | 346.2 | 217.0 |

# Check system nonlinearity




**Small PGA EQ (Event-4)**

$$DI_H = \sqrt{\frac{1}{n}\sum_{i=I}^{J}\left(\frac{|HG(f_i) - G(f_i)|}{G(f_i)}\right)^2} = 1.05$$




**Large PGA EQ (Event-5)**

$$DI_H = \sqrt{\frac{1}{n}\sum_{i=I}^{J}\left(\frac{|HG(f_i) - G(f_i)|}{G(f_i)}\right)^2} = 1.24$$



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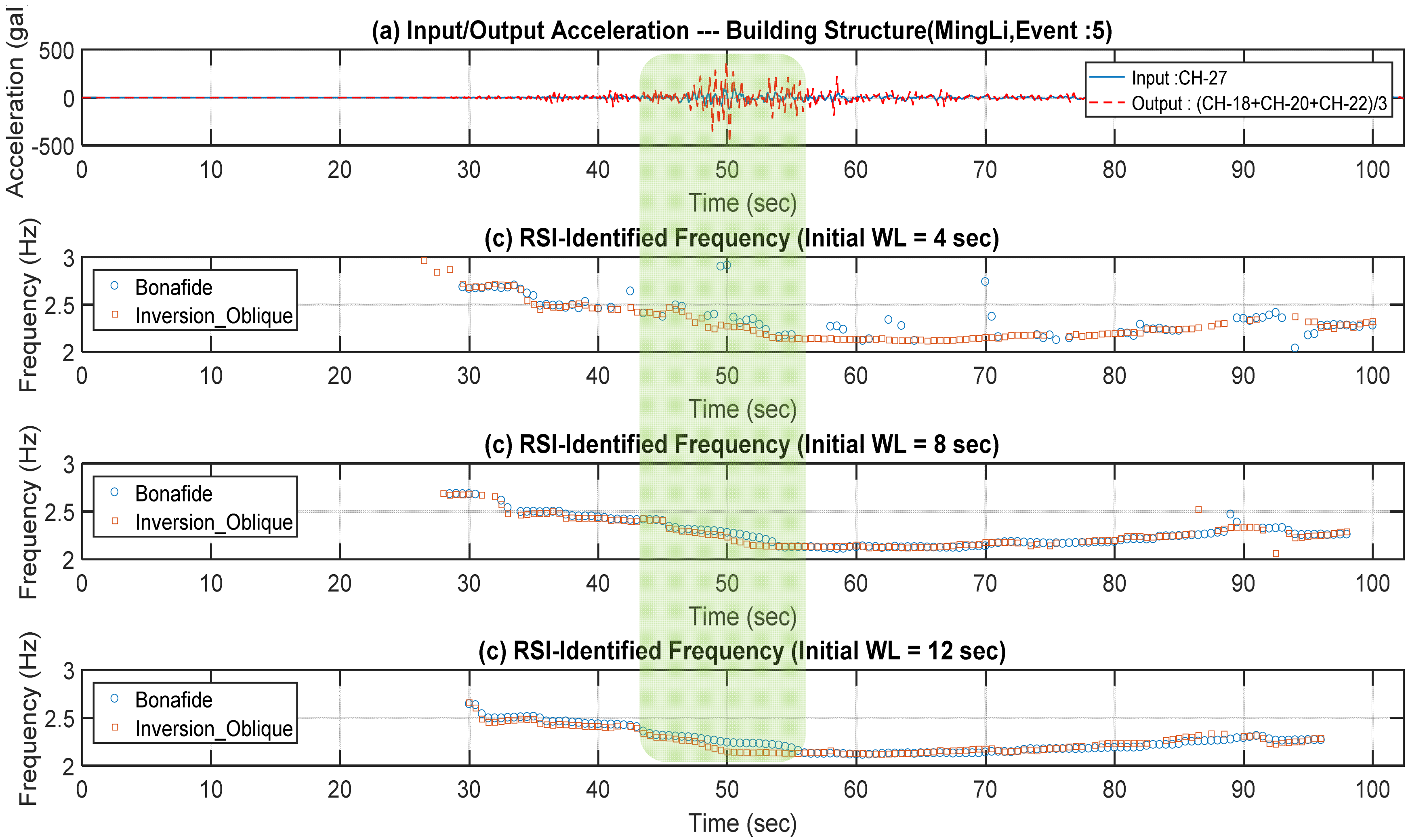
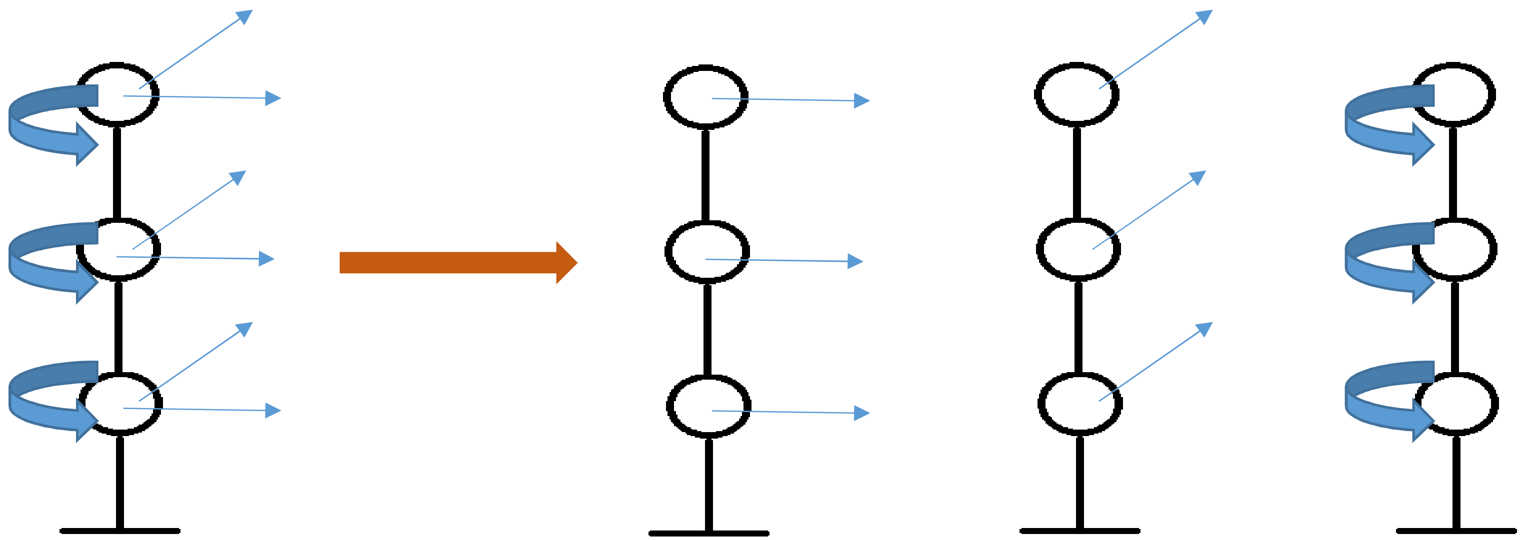
# Comparison on the result of identification between RSI-BonaFide & RSI Inversion-Oblique



Three-direction Model

Mono-direction Model



WL = 12sec

WL = 3sec

$$K\phi = \omega^2 M\phi$$

$$\mathbf{K}_{XX} = \mathbf{K}_{YY} = \begin{bmatrix} k_{x1}+k_{x2} & -k_{x2} & \mathbf{0} \\ -k_{x2} & k_{x2}+k_{x3} & -k_{x3} \\ \mathbf{0} & -k_{x3} & k_{x3} \end{bmatrix}$$

$$\mathbf{K}_{TT} = \begin{bmatrix} \left(\frac{1}{r_1^2}\right)(k_{\theta 1}+k_{\theta 2}) & -\frac{1}{r_1 r_2}k_{\theta 2} & 0 \\ -\frac{1}{r_1 r_2}k_{\theta 2} & \left(\frac{1}{r_2^2}\right)(k_{\theta 2}+k_{\theta 3}) & -\frac{1}{r_2 r_3}k_{\theta 3} \\ 0 & -\frac{1}{r_2 r_3}k_{\theta 3} & \left(\frac{1}{r_3^2}\right)k_{\theta 3} \end{bmatrix}$$

$$\boldsymbol{M}_{XX} = \boldsymbol{M}_{YY} = \boldsymbol{M}_{TT} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Assume r1 = r2 = r3



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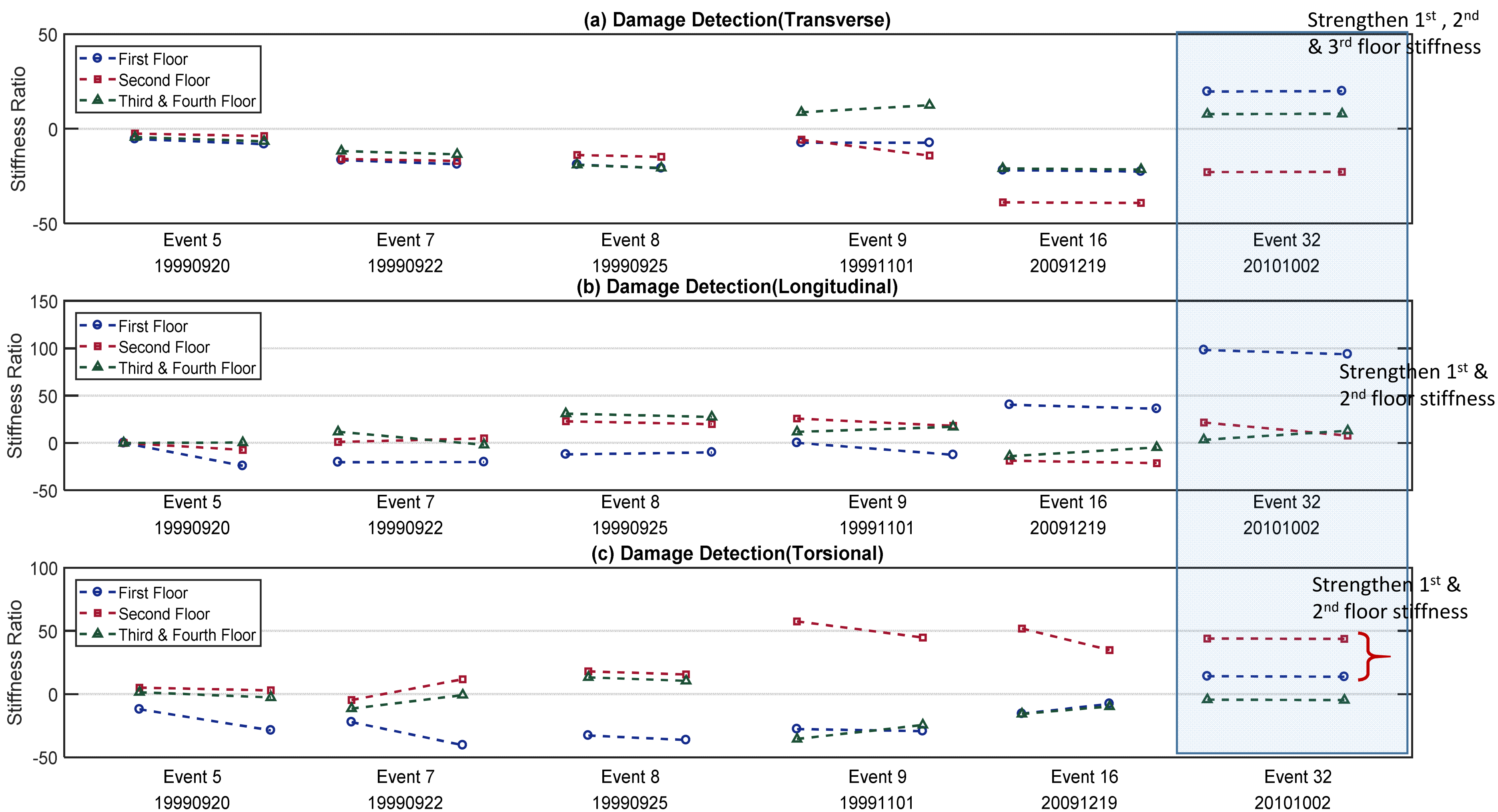
# Damage assessment of school building (from a series of seismic excitation





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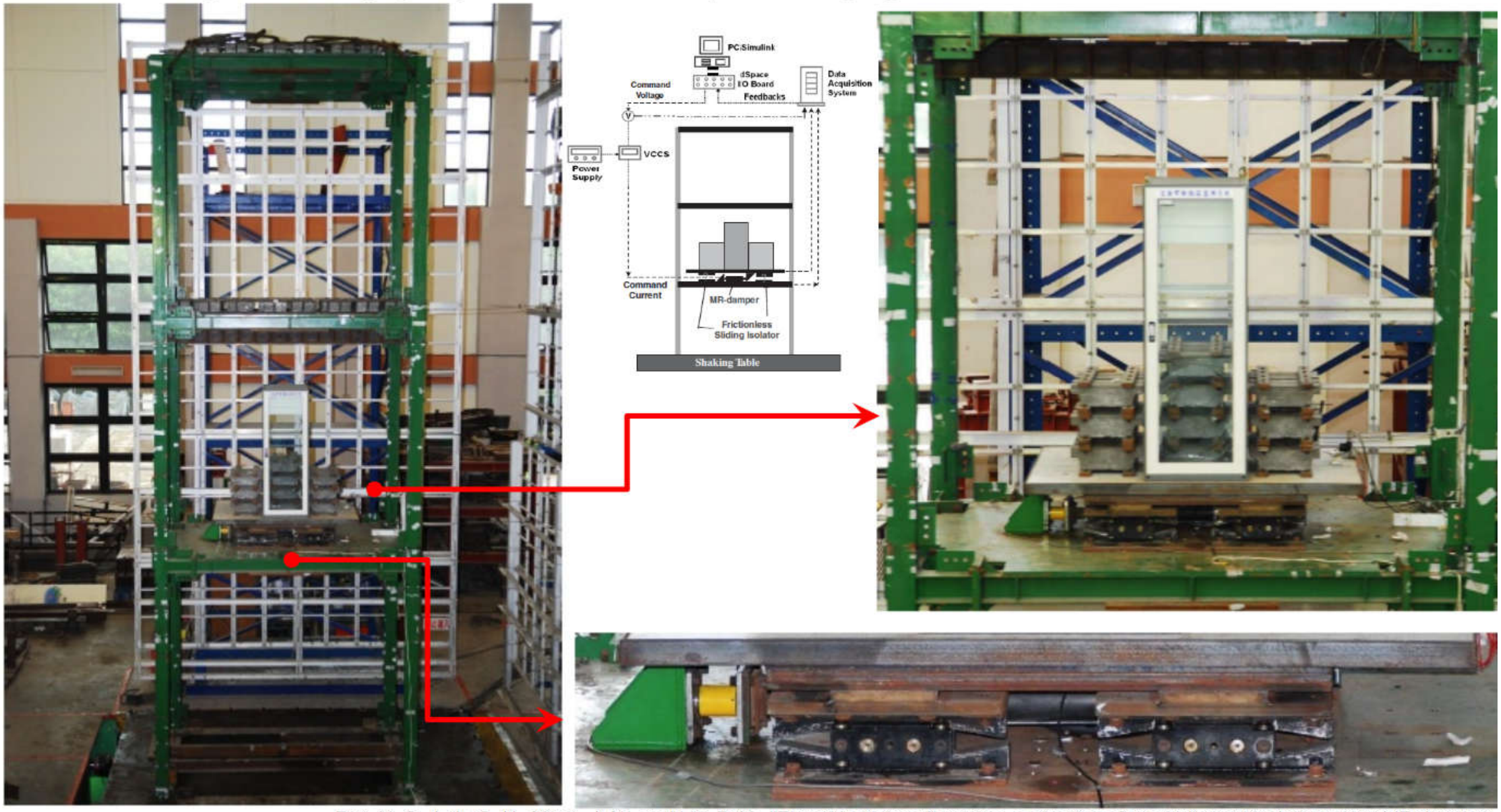
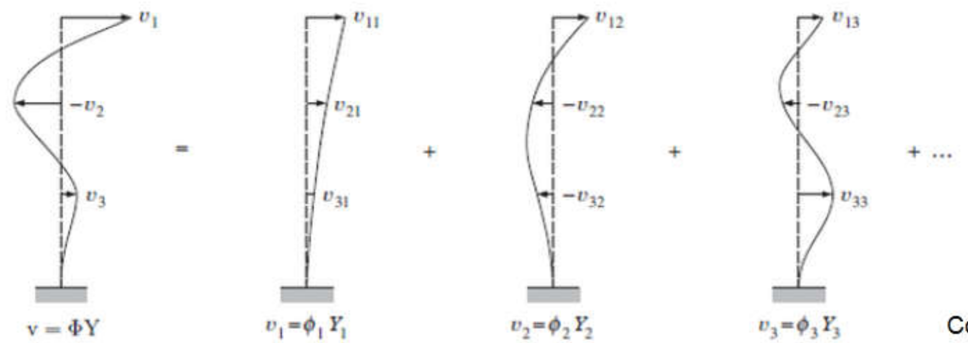
# Structural Control Research

- (left) steel frame with a light equipment at the first floor on NCREE shaking table; (right) control setup on equipment.

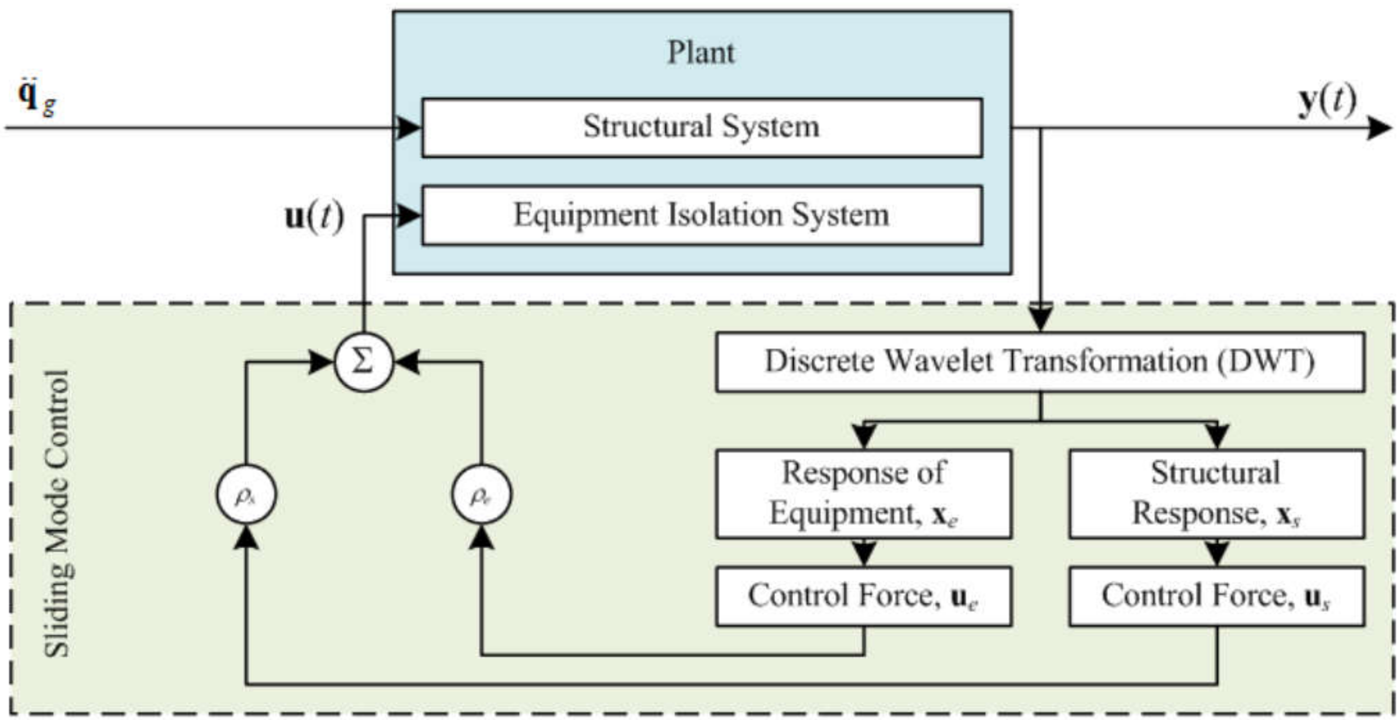



Fan, Y. C., Loh, C. H., Yang, J. N., and Lin, P. Y., "Experimental performance evaluation of an equipment isolation using MR dampers. Earthquake Engineering & Structural Dynamics, 38(3), 285-305 (2009

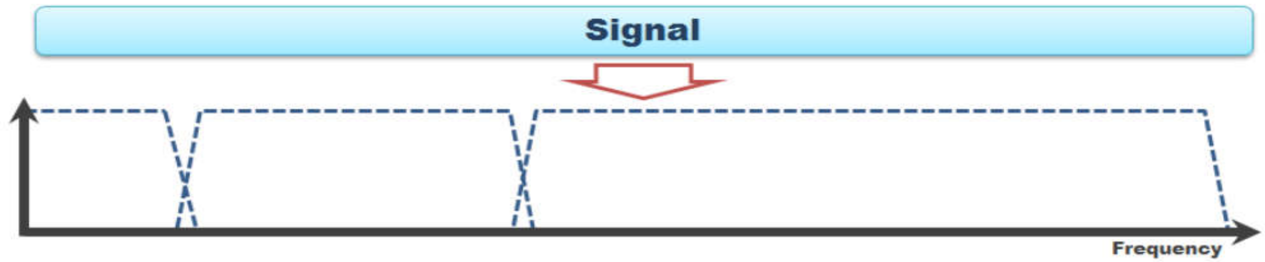
## Modal Analysis: The Superposition Principle of System




Courtesy to CSI Knowledge Base Website



- Online Wavelet Transform for Control




- WT step using a matrix algorithm (for a particular time window $\{\mathbf{q}\}$)

$$\mathbf{c}^1 = \mathbf{W}_d^1 \mathbf{q} = \begin{bmatrix} \langle \varphi_L \rangle & 0 & 0 & \cdots \\ \langle \varphi_H \rangle & 0 & 0 & \cdots \\ 0 & \langle \varphi_L \rangle & 0 & \cdots \\ 0 & \langle \varphi_H \rangle & 0 & \cdots \\ 0 & 0 & \langle \varphi_L \rangle & \cdots \\ 0 & 0 & \langle \varphi_H \rangle & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \mathbf{q} \qquad \mathbf{c}^2 = \mathbf{W}_d^2 \mathbf{c}^1 = \begin{bmatrix} \langle \varphi_L \rangle & 0 & 0 & \cdots \\ 1 & 0 & 0 & \cdots \\ 0 & \langle \varphi_H \rangle & 0 & \cdots \\ 0 & 1 & 0 & \cdots \\ 0 & 0 & \langle \varphi_L \rangle & \cdots \\ 0 & 0 & 1 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \mathbf{c}^1 \quad \cdots\cdots\cdots$$

To $j$-th level decomposition

$$\mathbf{c}^J = \mathbf{W}_d \mathbf{q} = \prod_{i=1}^{J} \mathbf{W}^i{}_d \mathbf{q}$$

$$\mathbf{q} = \mathbf{W}_r^1 \mathbf{c}^1 \quad \cdots\cdots\cdots \quad \mathbf{q} = \mathbf{W}_r \mathbf{c}^J = \prod_{i=1}^{J} \mathbf{W}^i{}_r \mathbf{c}^J$$

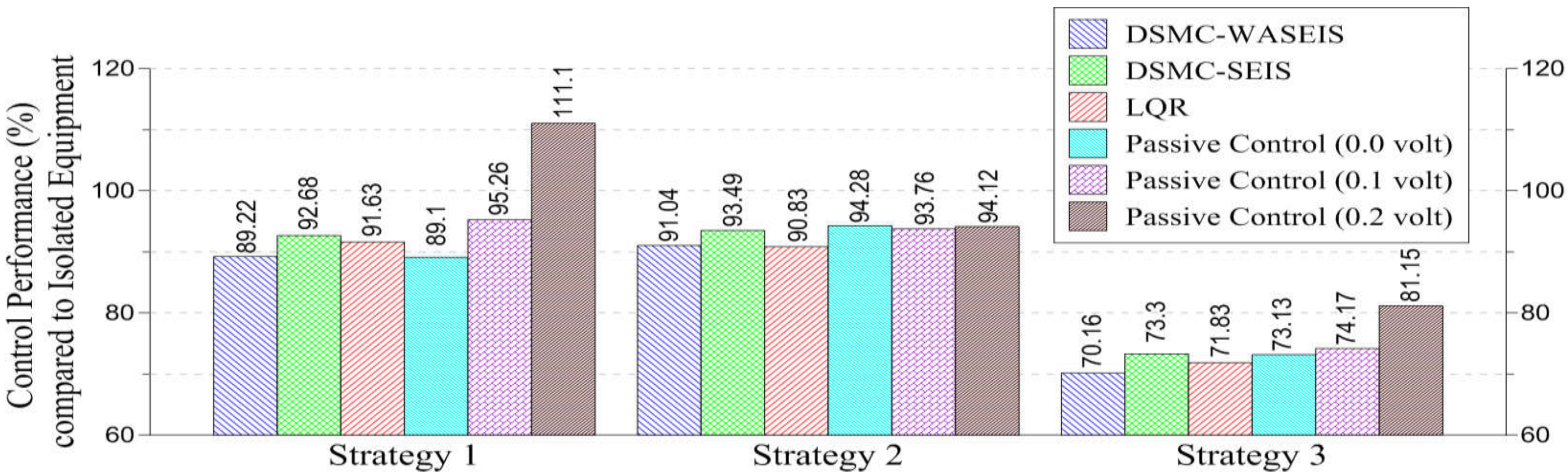
Online matrix operation (reconstructed signal after wavelet transform to $j$-th level)

$$\hat{\mathbf{q}} = \mathbf{W}_r \mathbf{H} \mathbf{W}_d \mathbf{q} = \mathbf{W} \mathbf{q}$$

**An index matrix, H, can be introduced to assign which approximations or details need to be selected for reconstructing time series**

(1) Online Wavelet-based Decentralized Sliding Mode Control with Static Output Feedback (Wavelet-based DSMC-SOF)

(2) Online Wavelet-based Decentralized Sliding Mode Control considering SDOF Equipment Isolation System (Wavelet-based DSMC-SEIS)




| | Control Strategies | Objective Functions |
|---|---|---|
| (1) | Best Reduction on Absolute Acceleration of Equipment | $J_1 = \min J_b(4)$ |
| (2) | Best Reduction on Inter-story Drift Ratio of Frames | $J_2 = \min\{\max[J_a(i)]\} \quad i \in 1 \sim 3$ |
| (3) | Balance on Both | $J_3 = \min \left\| [J_c(i), J_d(i)] \right\|_2 \quad i \in 1 \sim 4$ |



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# Conclusions

1. Develop a more effective auto-seismic response monitoring system for the assessment of structural safety
2. Implement the current (or updated) algorithm to several seismic building monitoring.
3. Study the compensation algorithm on the discontinuity of frequency estimation using result from RSI, and implement for structural damage assessment using simplified model.
4. Wavelet analysis ensure the stability of decentralized SMC.
5. Proposed method can control various modes differently and reduce the response of frame.
6. It only use very limited feedback and secure feasibility and reliability.



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# Thank you for your attention !

## *Questions ?*