2018

The International Joint Workshop

# Structural Design of High-Rise Buildings with Passive Control Devices

Aula Barat, ITB Campus, 20-21 August 2018

INSTITUT TEKNOLOGI BANDUNG
1920

NCREE

AARGI
ASOSIASI AHLI REKAYASA KEGEMPAAN INDONESIA

2018

The International Joint Workshop

# Structural Design of High-Rise Buildings with Passive Control Devices

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# Activities of NCREE on Research and Applications of Passive Control Technology

## Dr. Shyh-Jiann Hwang

Director General of NCREE and Professor at the Department of Civil Engineering of NTU

Experiences

- Deputy Director, NCREE, NARL
- President, CTSEE
- President, CSSE
- Director, CEER, NTU
- Professor, NTUST

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Dr. Shyh-Jiann Hwang is a Professor of Civil Engineering at the National Taiwan University, and also serves as the Director of the National Center for Research on Earthquake Engineering, Taipei, Taiwan. He received his PhD from the University of California at Berkeley. He has been the president of the Chinese Taiwan Society for Earthquake Engineering (CTSEE) from 2014 to 2018, and also the president of the Chinese Society of Structural Engineering (CSSE) from 2008 to 2012.

Dr. Shyh-Jiann Hwang is a member of Joint ACI-ASCE Committee 352, Joints and Connection in Monolithic Concrete Structures. His research interests include seismic design of reinforced concrete structure, shear behavior of reinforced concrete members, and seismic retrofitting of reinforced concrete structures. He is also a Principal Investigator for Taiwan seismic code for reinforced concrete structures, school building retrofitting program, pioneer research project for nuclear power plant, and hazard risk evaluation for the support structure of offshore wind farms.

NARLabs 國家實驗研究院
國家地震工程研究中心

**2018 The International Joint Workshop**
**Structural Design of High-Rise Buildings with Passive Control Devices**

# Activities of NCREE on Research and Applications of Passive Control Technology

## Shyh-Jiann Hwang

NCREE

Director
National Center for Research on Earthquake Engineering

Professor
National Taiwan University

**August 20, 2018**

承諾・熱情・創新

www.narlabs.org.tw

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# Outline

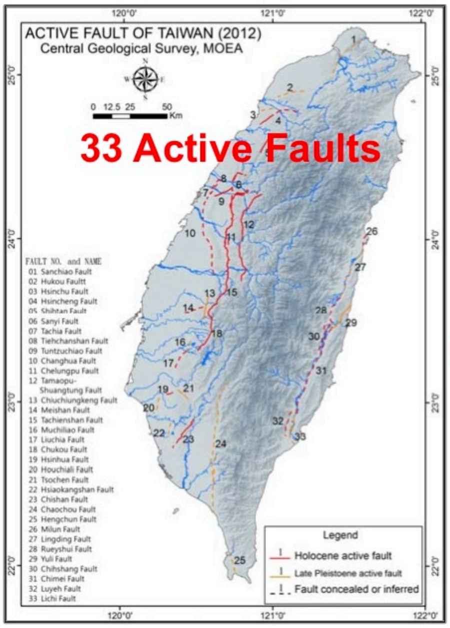
- **History and Purpose of NCREE**
- **Testing Facilities at NCREE**
  - ✓ **Taipei Lab**
  - ✓ **Tainan Lab**

# NCREE

## Taipei Lab

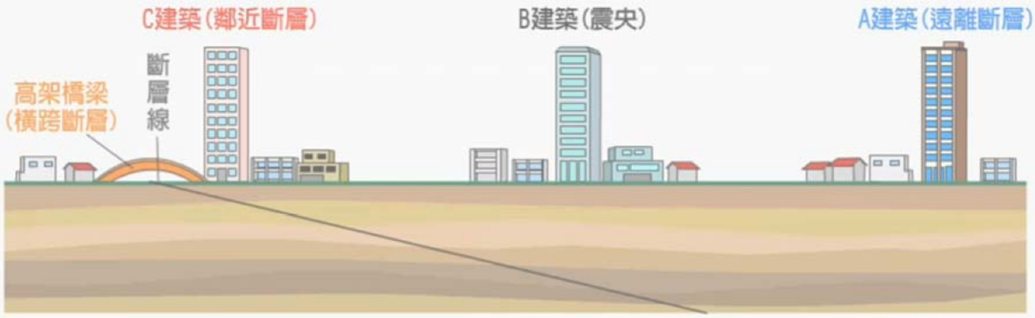
- **Project awarded in 1990**
- **Start building in 1993**
- **Opening ceremony in 1998**

# Threats of Near Fault Ground Motions



- **2.5 million buildings and 8.6 million people within 10 km around active faults**
- **Nearly 1/3 population of Taiwan under threats of near fault ground motions**

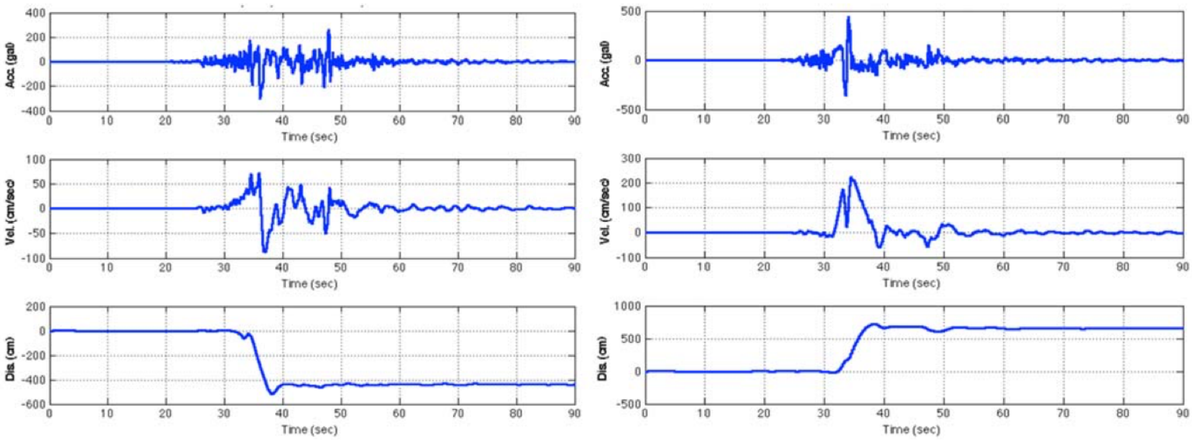
# Features of Near Fault Ground Motions (I)



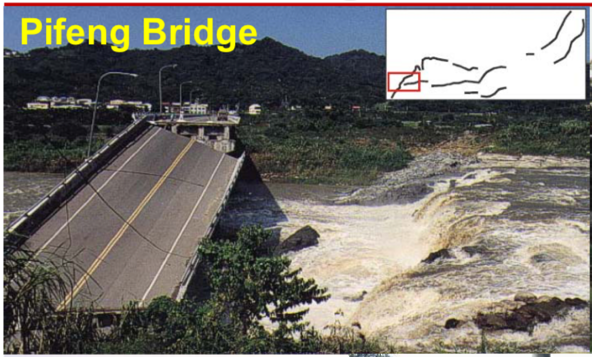
- **Large permanent ground displacement**

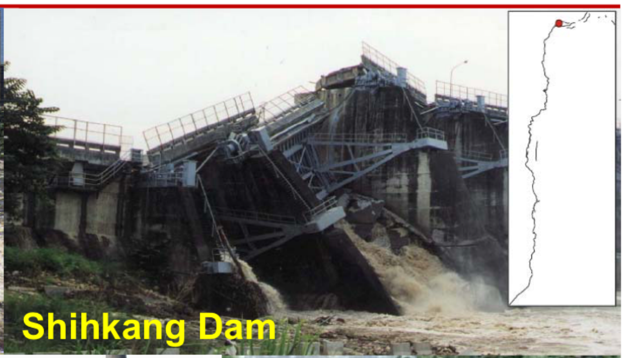
# Features of Near Fault Ground Motions (II)

- **High velocity pulse**
- **Long period of pulse**



# Effects of Near Fault Ground Motions on Buildings and Infrastructures


**Pifeng Bridge**


**Shihkang Dam**


**Kuang Fu Junior High School**


**Railroad**

# NCREE Tainan Lab (I)

- Memorandum of Understanding (MOU) between NARL and NCKU signed in 2013
- Construction of main building started in 2014 and completed in 2016 (Budget: ~17M USD)
- Installation of major test facilities completed in 2017 (Budget: ~27M USD)
- Grand Opening on Aug. 9, 2017

# NCREE Tainan Lab (II)

NARLabs 國家實驗研究院
國家地震工程研究中心
National Center for Research on Earthquake Engineering

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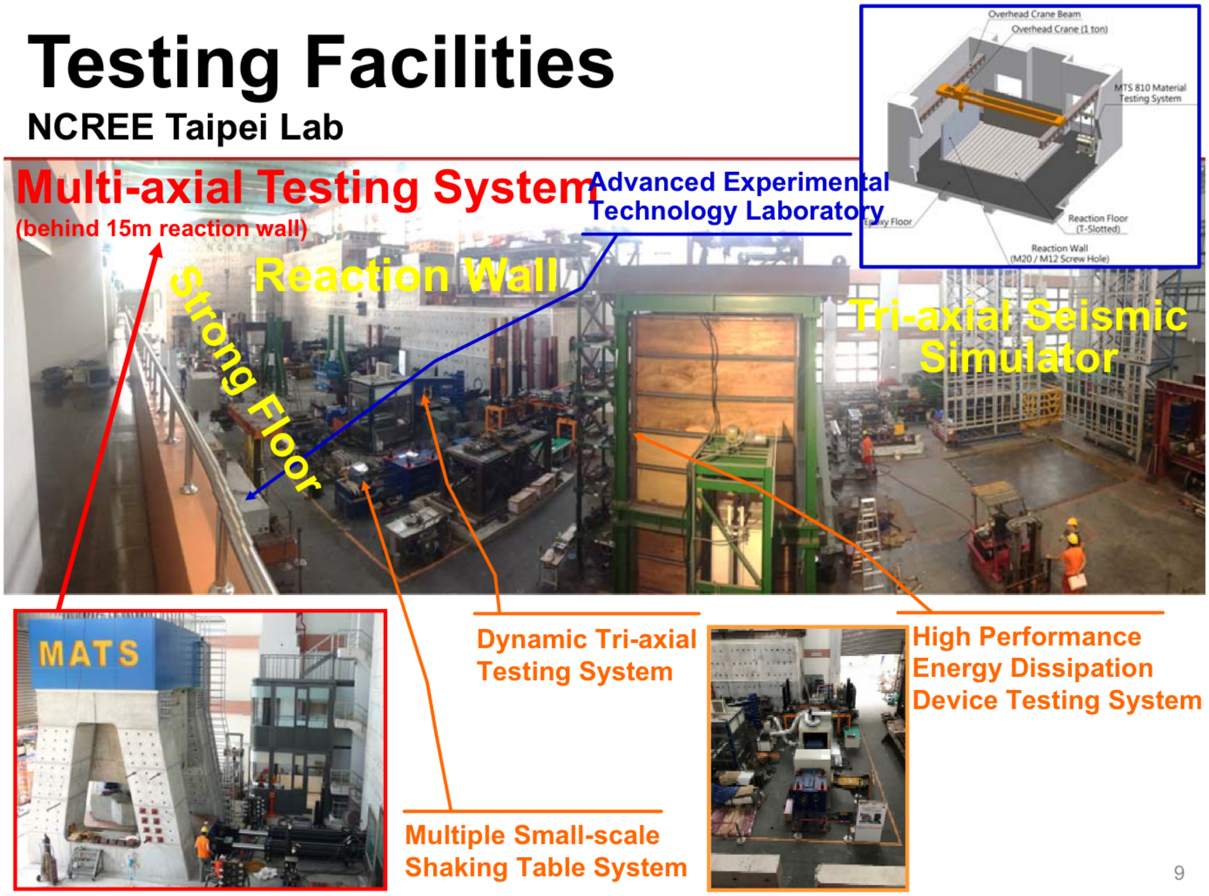
# Testing Facilities

NCREE Taipei Lab



**Multi-axial Testing System**
(behind 15m reaction wall)

**Advanced Experimental Technology Laboratory**

**Reaction Wall**

**Strong Floor**

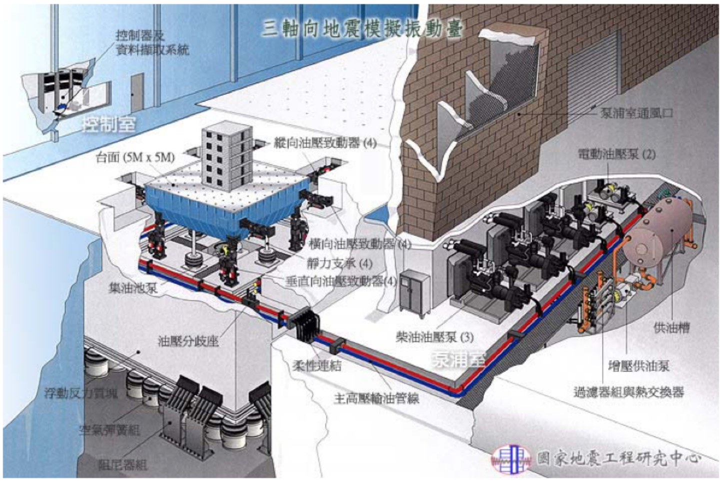
**Tri-axial Seismic Simulator**

**Dynamic Tri-axial Testing System**

**High Performance Energy Dissipation Device Testing System**

**Multiple Small-scale Shaking Table System**

# Tri-axial Seismic Simulator



| 項目 |  | 規格 |
|---|---|---|
| 最大載重 (公斤)<br>Maximum Specimen Weight (kg) |  | 50,000 |
| 最大扭矩 (公斤-公尺)<br>Overturning Moment (kg-m) |  | 150,000 |
| 頻率範圍<br>Frequency Range (Hz) | 最大值<br>Maximum | 50 |
|  | 最小值<br>Minimum | 1 |
| 最大位移量<br>Max. Displacement (mm) | 縱軸 (X向)<br>Longitudinal | ±250 |
|  | 橫軸 (Y向)<br>Lateral | ±100 |
|  | 垂直軸 (Z向)<br>Vertical | ±100 |
| 最大速度<br>Max. Velocity (mm/sec) | 縱軸 (X向)<br>Longitudinal | ±1,000 |
|  | 橫軸 (Y向)<br>Lateral | ±600 |
|  | 垂直軸 (Z向)<br>Vertical | ±500 |
| 最大加速度<br>Max. Acceleration (g) | 縱軸 (X向)<br>Longitudinal | 2 |
|  | 橫軸 (Y向)<br>Lateral | 1.5 |
|  | 垂直軸 (Z向)<br>Vertical | 1 |
| 振動台尺寸<br>Table Size |  | 5m x 5m |

SYSTEM CERTIFICATION ISO 9001:2000 SGS

TAF
Calibration Laboratory
1180

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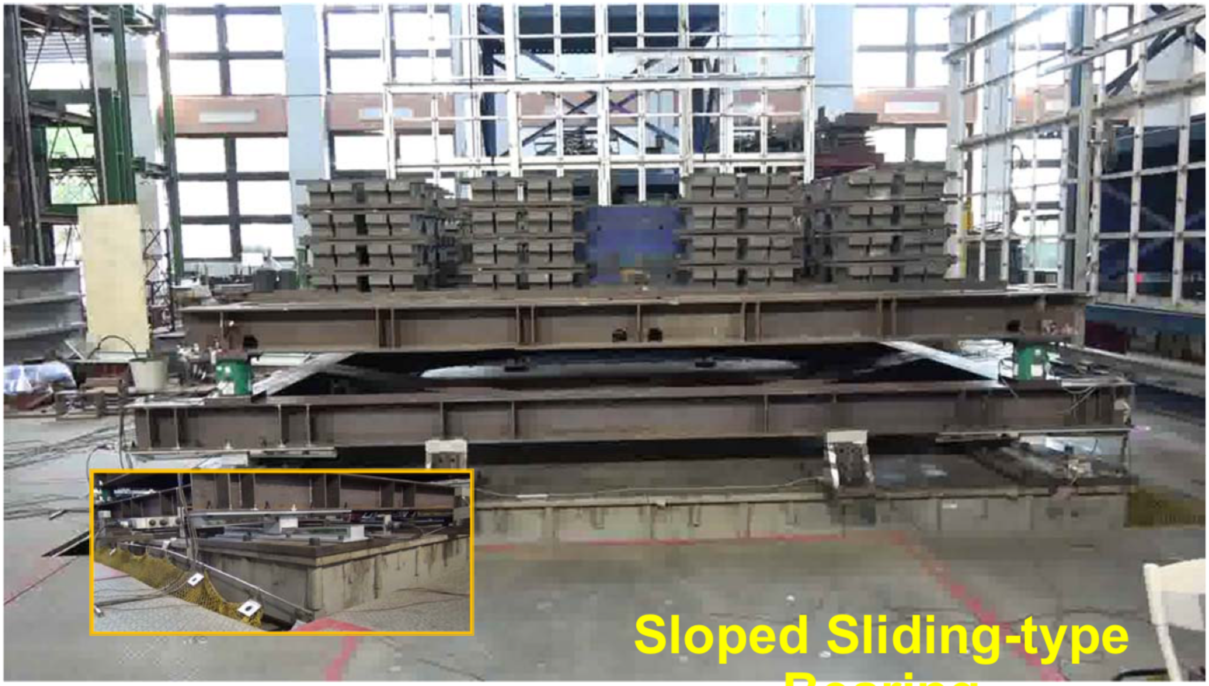
# Test Experience

# Demonstration Test (I)

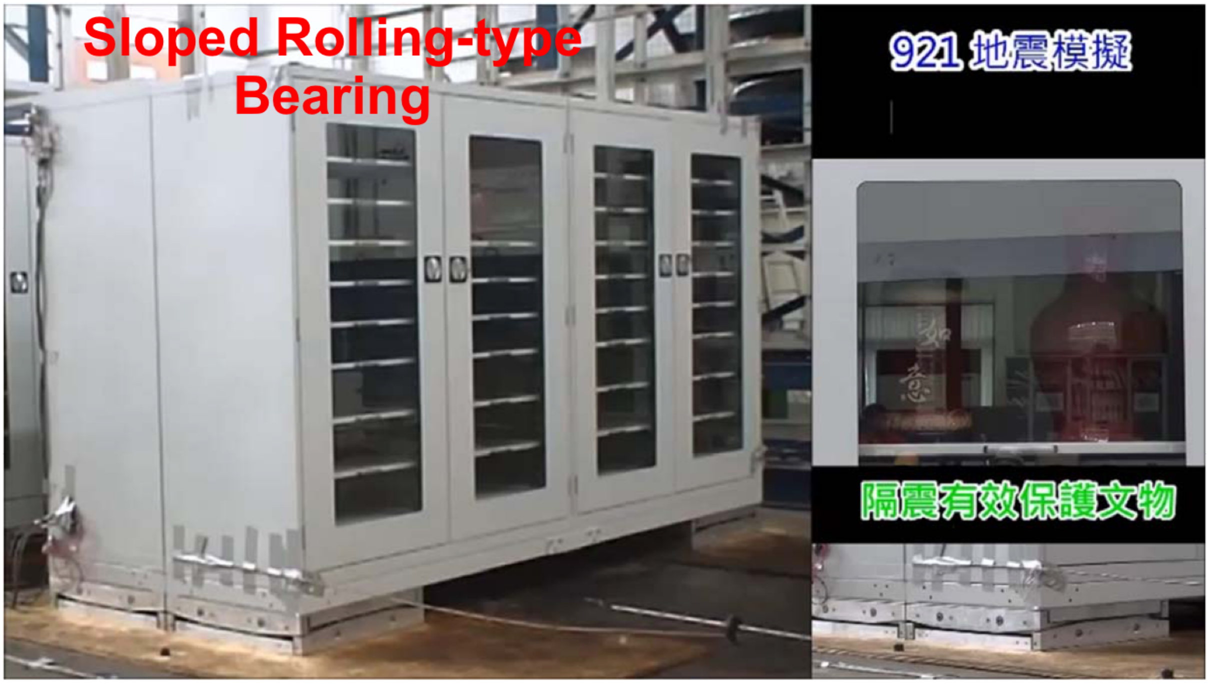
Building Mass Damper

# Demonstration Test (II)



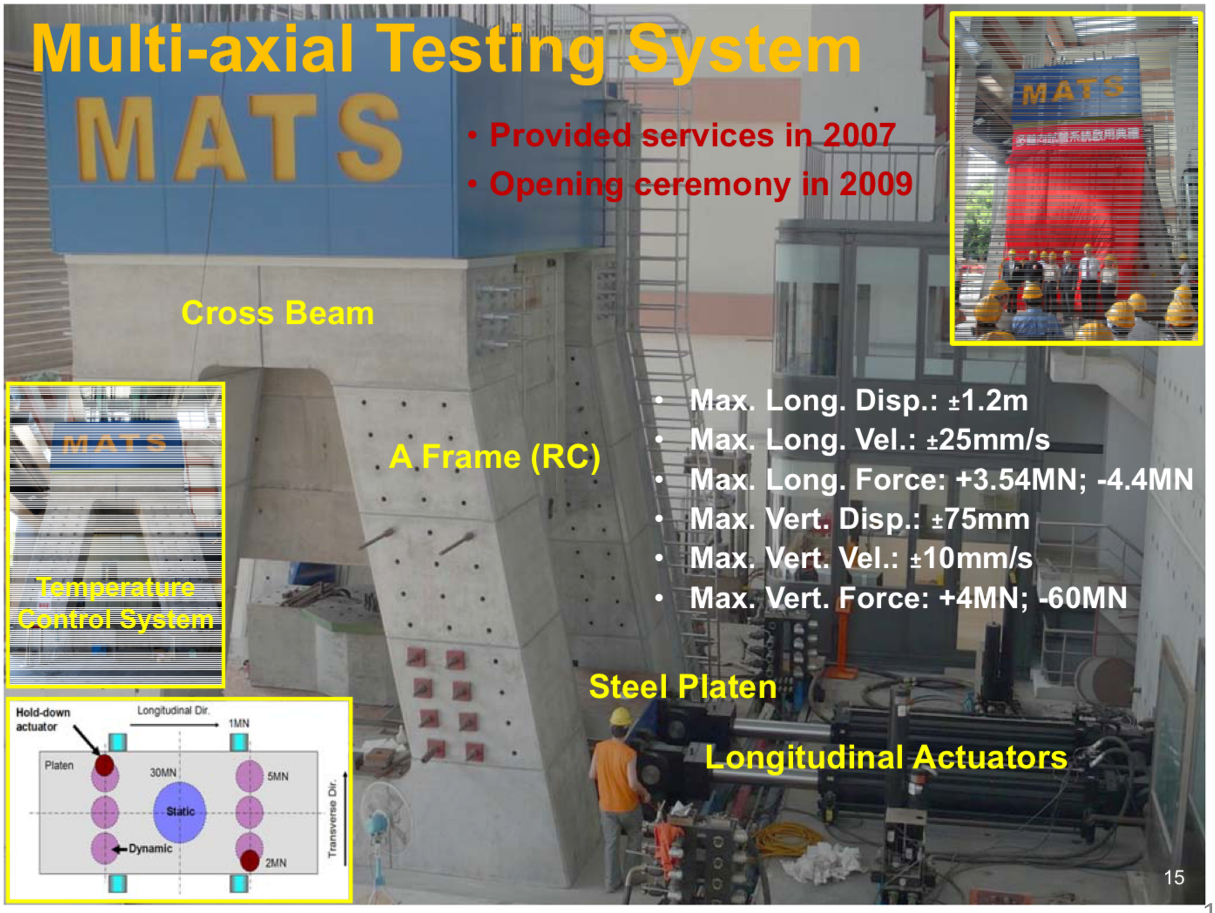
Sloped Sliding-type Bearing

# Demonstration Test (III)



# Multi-axial Testing System

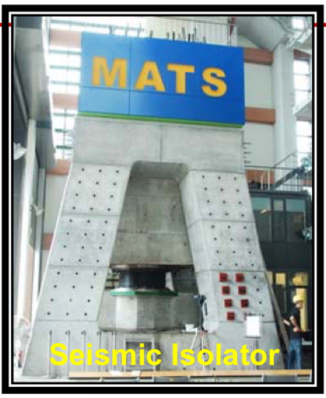
- Provided services in 2007
- Opening ceremony in 2009



- Max. Long. Disp.: ±1.2m
- Max. Long. Vel.: ±25mm/s
- Max. Long. Force: +3.54MN; -4.4MN
- Max. Vert. Disp.: ±75mm
- Max. Vert. Vel.: ±10mm/s
- Max. Vert. Force: +4MN; -60MN

# Test Experience


Coupled Steel Plate Shear Wall

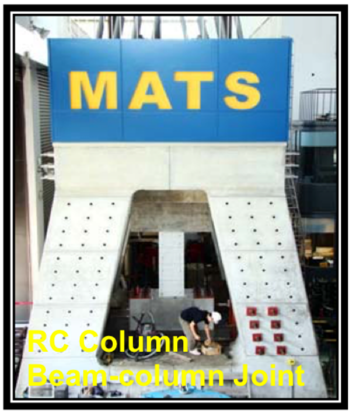


Seismic Isolator

VE Damper


BRB


Low-yield Steel Shear Panel



RC Column Beam-column Joint

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# Demonstration Test (I)


Lead Rubber Bearing

# Demonstration Test (II)

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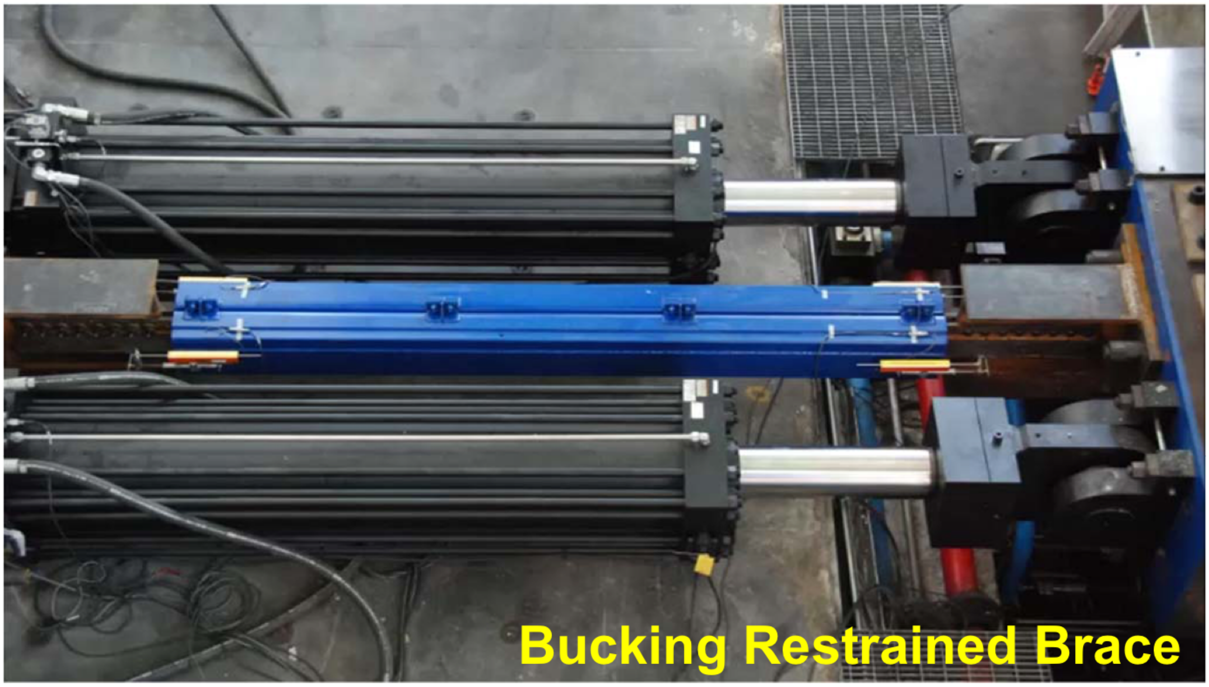
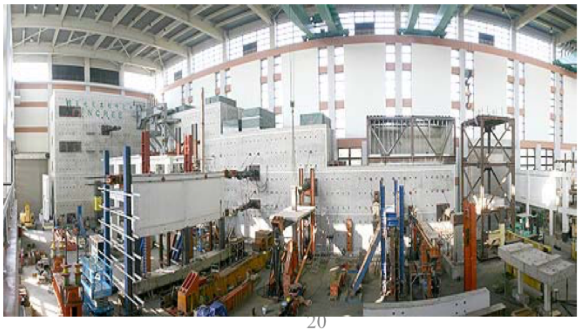
# Demonstration Test (III)



# Reaction Wall and Strong Floor

- Max. hydraulic flow rate: 1325gpm
- 28 hydraulic outlets
- Quasi-static cyclic loading tests
- Pseudo-dynamic tests
- Hybrid simulation



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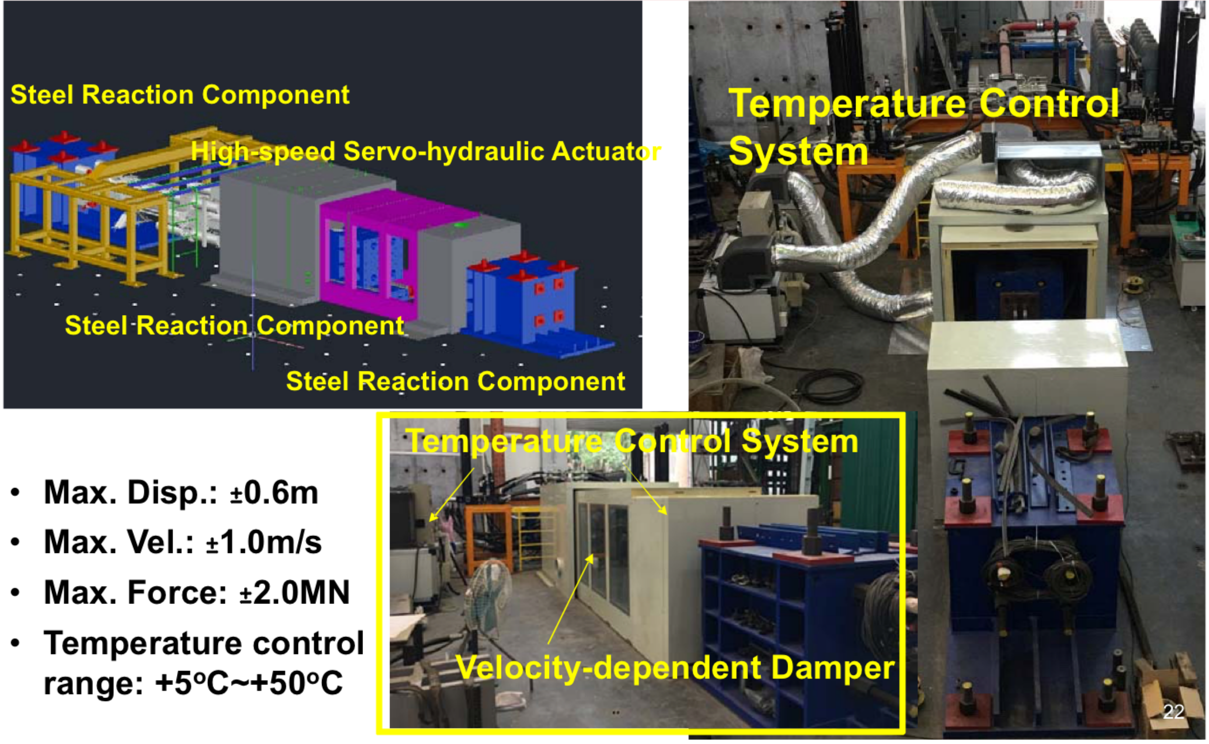
# Test Experience

# High Performance Energy Dissipation Device Testing System



- Max. Disp.: ±0.6m
- Max. Vel.: ±1.0m/s
- Max. Force: ±2.0MN
- Temperature control range: +5°C~+50°C

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# Demonstration Test (I)

# Demonstration Test (II)

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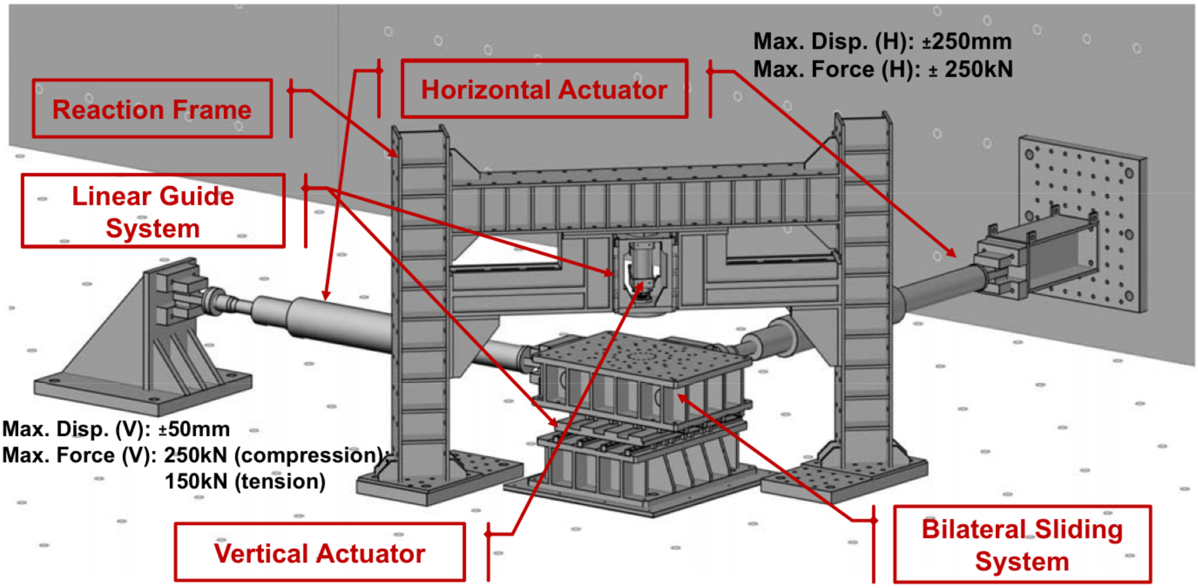
# Dynamic Tri-axial Testing System



**Reaction Frame**

**Linear Guide System**

**Horizontal Actuator**

Max. Disp. (H): ±250mm
Max. Force (H): ± 250kN

Max. Disp. (V): ±50mm
Max. Force (V): 250kN (compression);
150kN (tension)

**Vertical Actuator**

**Bilateral Sliding System**

## Different Plane Orbits

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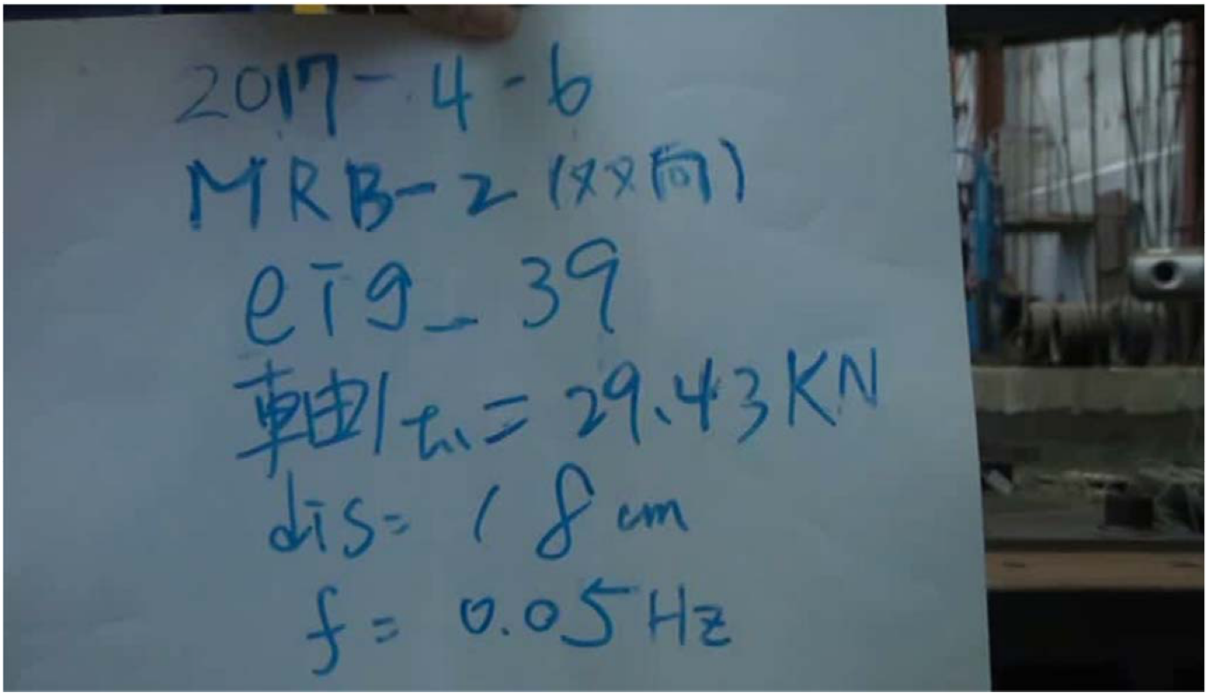
# Demonstration Test (I)

# Demonstration Test (II)



2017-4-6
MRB-2 (XX向)
eig_39
軸力=29.43KN
dis= 18cm
f= 0.05Hz

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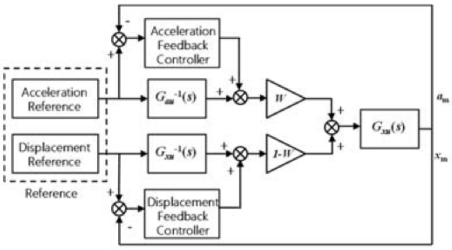
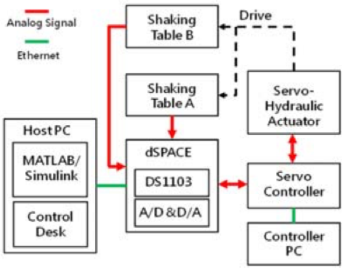
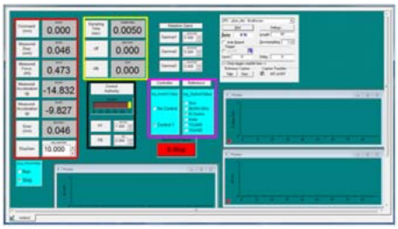
# Multiple Small-scale Shaking Table System







# Demonstration Test

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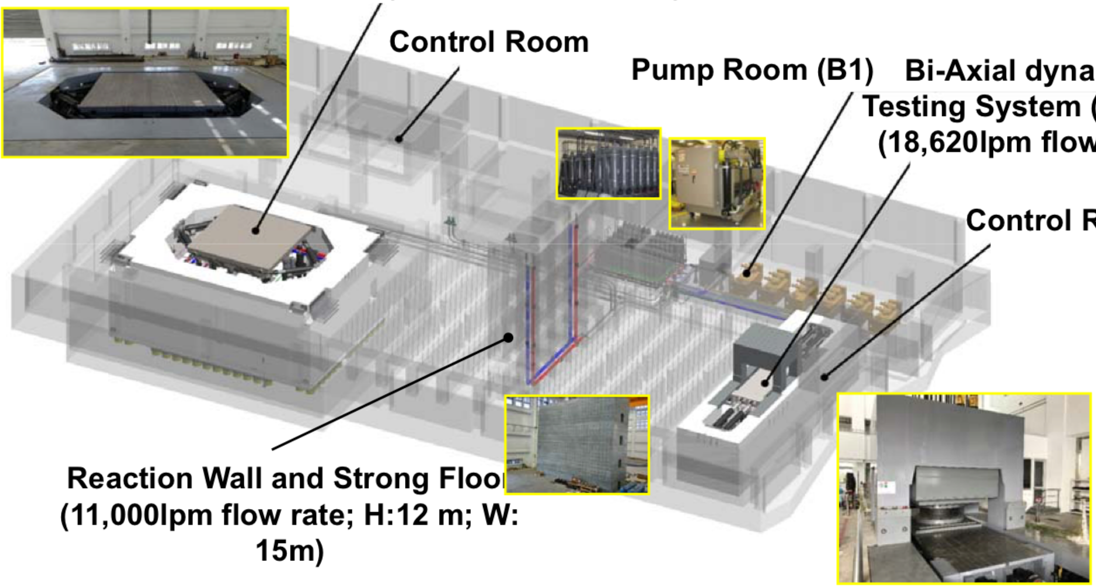
# Testing Facilities

## NCREE Tainan Lab



Long Stroke and High Speed Earthquake Simulator (26,000lpm flow rate)

Control Room

Pump Room (B1)

Bi-Axial dynamic Testing System (BATS) (18,620lpm flow rate)

Control Room

Reaction Wall and Strong Floo (11,000lpm flow rate; H:12 m; W: 15m)

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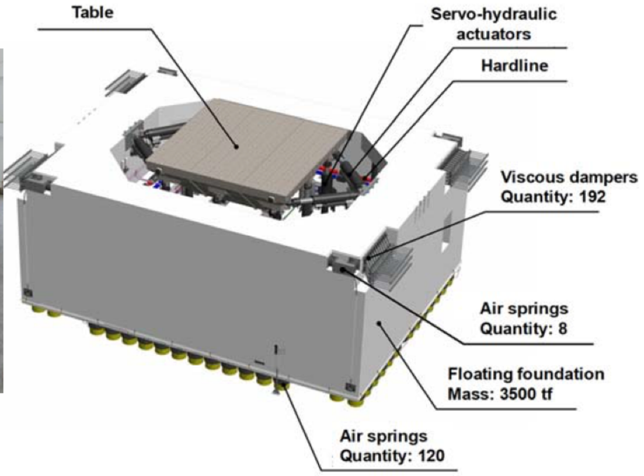
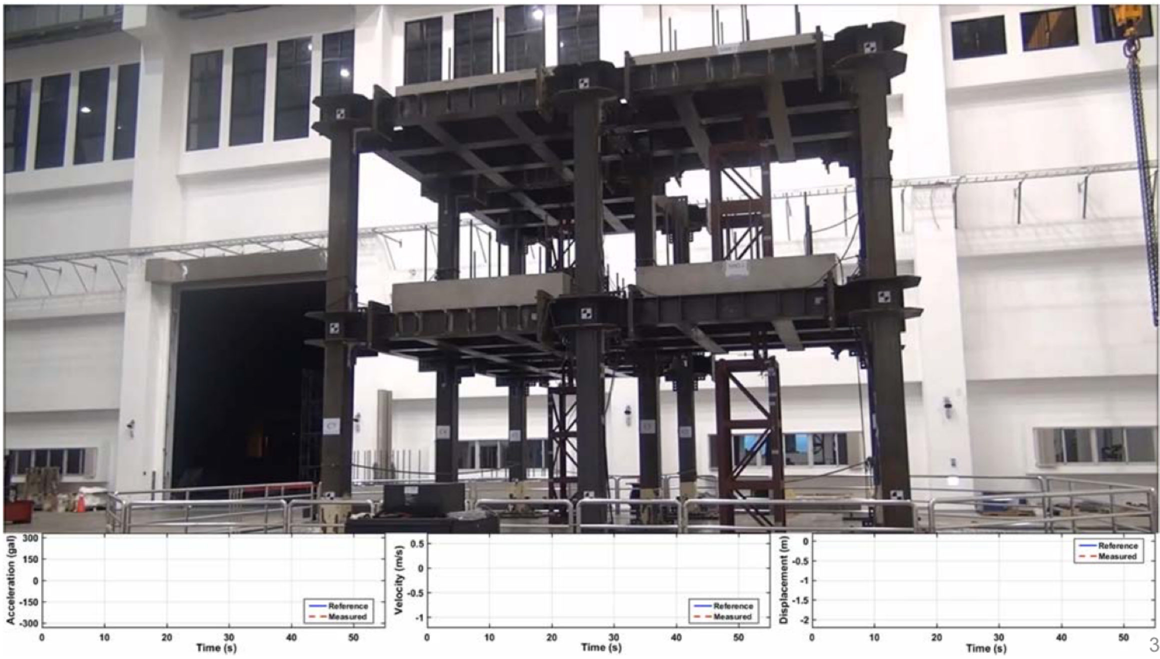
# Long Stroke and High Speed Earthquake Simulator



| Site | Size (m) | Max Stroke (m) | Max. Velocity (m/s) | Max Acceleration (g) | Max payload (ton) |
|---|---|---|---|---|---|
| Tainan Lab | 8 x 8 | H±1<br>V±0.4 | H±2<br>V±1 | H±2.5<br>V±3.0 | 250 |
| Taipei Lab | 5 x 5 | H±0.25<br>V±0.1 | H±1<br>V±0.5 | H±1.5<br>V±1.0 | 50 |

# Demonstration Test (I)

## 1999 921 Chi-Chi EQ (TCU052)



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# Demonstration Test (II)

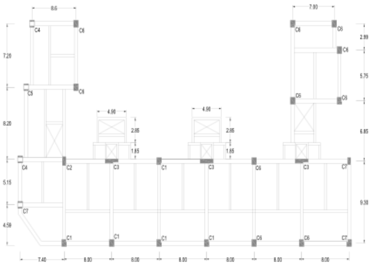
## 1999 921 Chi-Chi EQ (TCU052)

# Test Purpose

## Mixed-use Residential and Commercial Building

Features of collapsed building in Meinong EQ

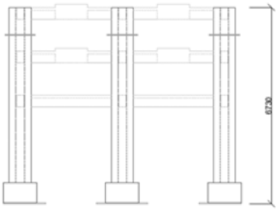
- Soft story
- Weak story
- Low redundancy
- 115 of 117 killed in this building



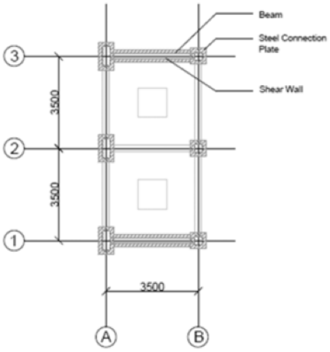
# Test Specimen

## 3-story RC building

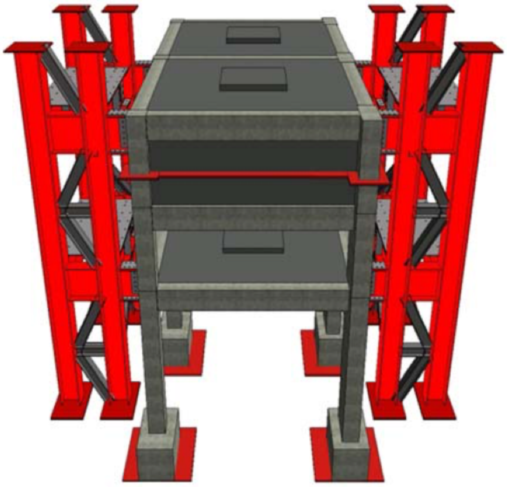
- 1/2 scale with non-ductile detailing
- High ceiling at 1st floor and soft story behavior
- Weight: 67 ton (97 ton w/ fail-safe frame)
- 1st modal frequency: 2.5 Hz



**Elevation view**

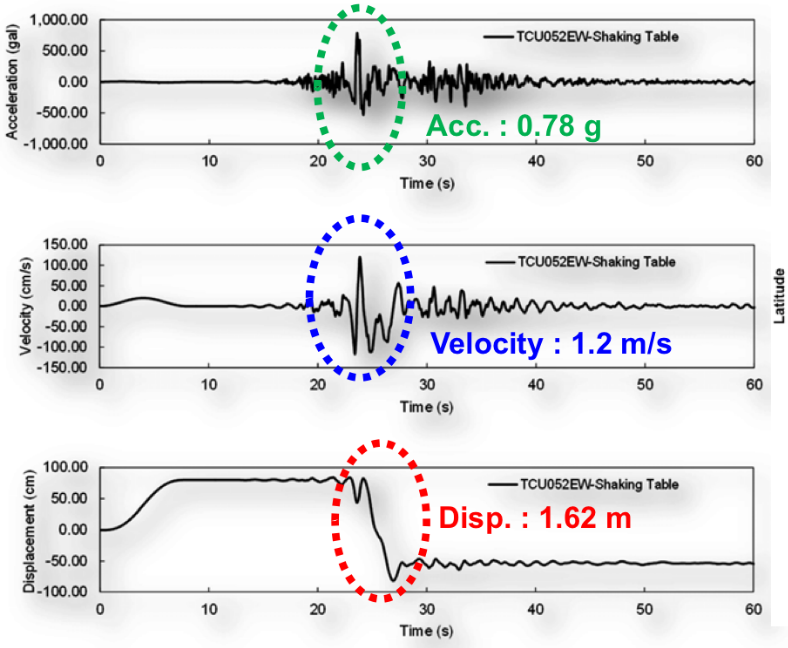


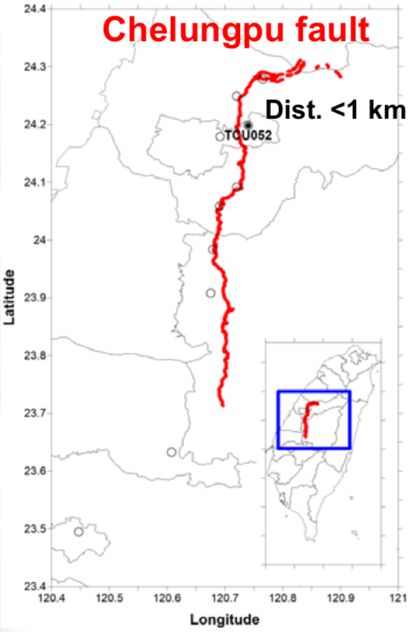
**Plan view**



# Input Ground Motion

## 1999 921 Chi-Chi EQ (TCU052)





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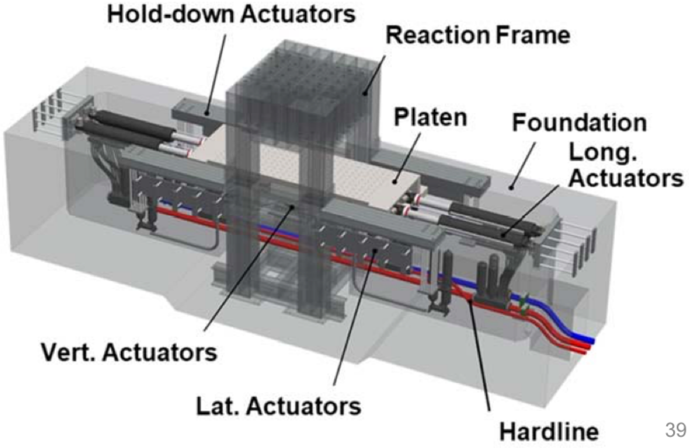
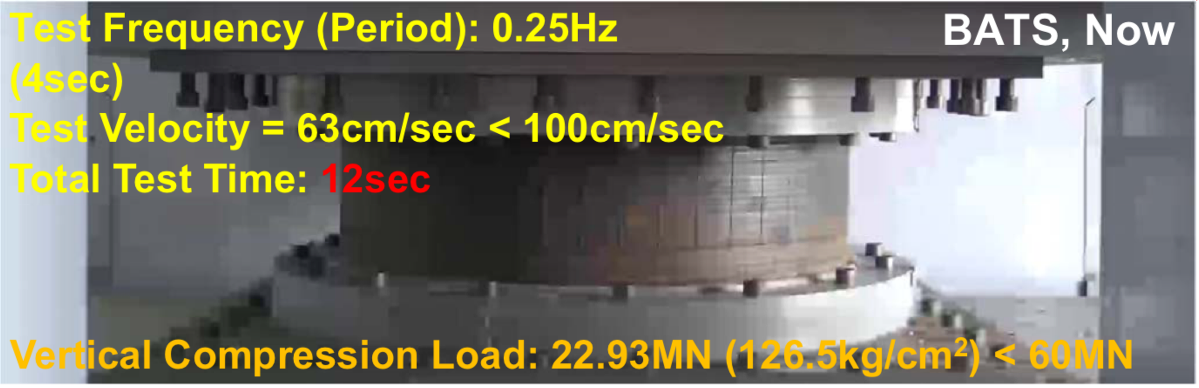
# Bi-Axial dynamic Testing System (BATS)

| | |
|---|---|
| Static Vert. Compression Force (MN) | 30 |
| Dynamic Vert. Compression Force (MN) | 30 |
| Total Vert. Compression Force (MN) | 60 |
| Vert. Tension Force (MN) | 8 |
| Vert. Velocity (+/- m/s) | 0.15 |
| Vert. Displacement (+/- mm) | 75 |
| Long. Force (+/- MN) | 4 |
| Long. Velocity (+/- m/s) | 1 |
| Long. Displacement (+/- mm) | 1200 |
| Roll, Pitch, Yaw (+/- deg) | 2 |



# Demonstration Test (I)



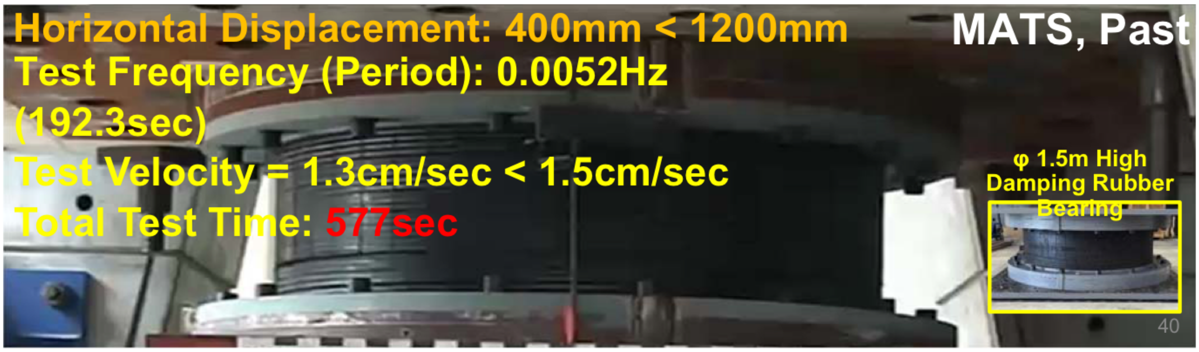
Test Frequency (Period): 0.25Hz (4sec)

Test Velocity = 63cm/sec < 100cm/sec

Total Test Time: 12sec

Vertical Compression Load: 22.93MN (126.5kg/cm$^2$) < 60MN

**BATS, Now**



Horizontal Displacement: 400mm < 1200mm

Test Frequency (Period): 0.0052Hz (192.3sec)

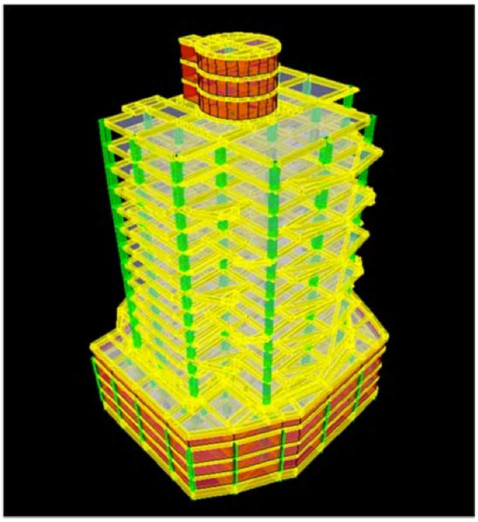
Test Velocity = 1.3cm/sec < 1.5cm/sec

Total Test Time: 577sec

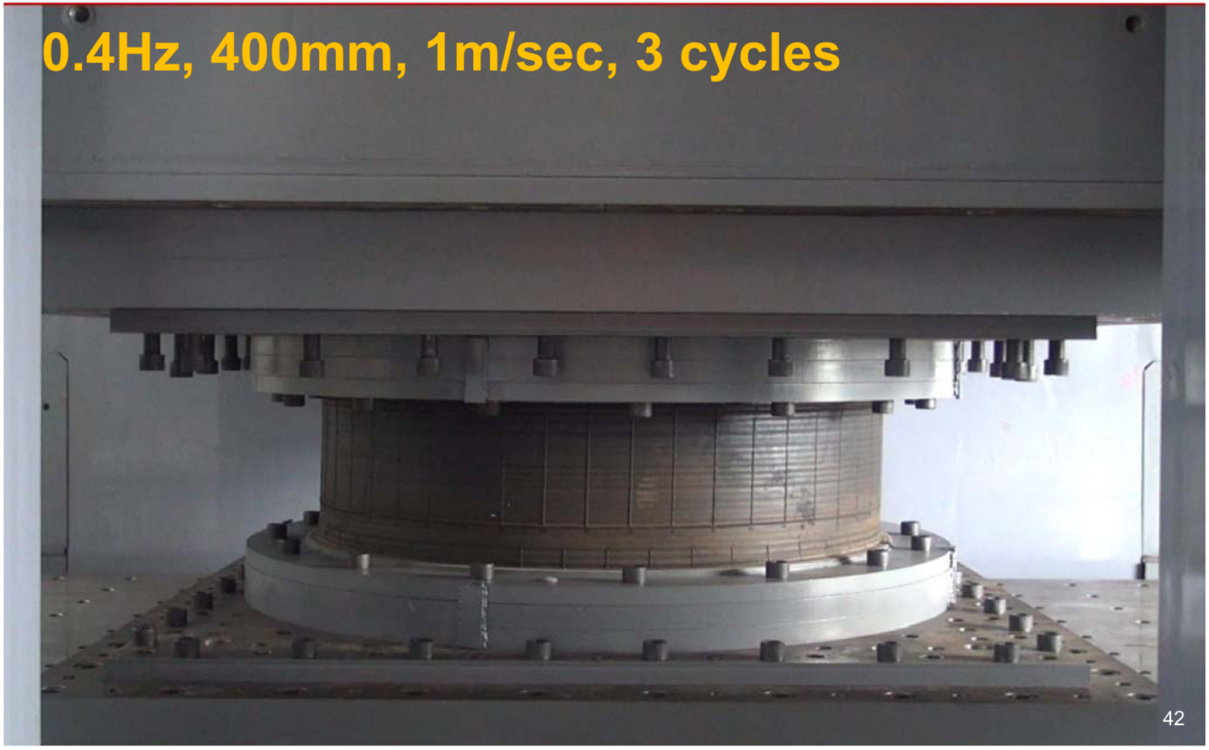
**MATS, Past**

# Test Purpose

- Site: Taipei Basin II ($S_{DS}$ = 0.6, $S_{MS}$ = 0.8, $T_0$ = 1.3sec)
- Architecture: B4F~12F
- Structural System: RC + Seismic Isolation
- Isolation System: HDRB + FVD

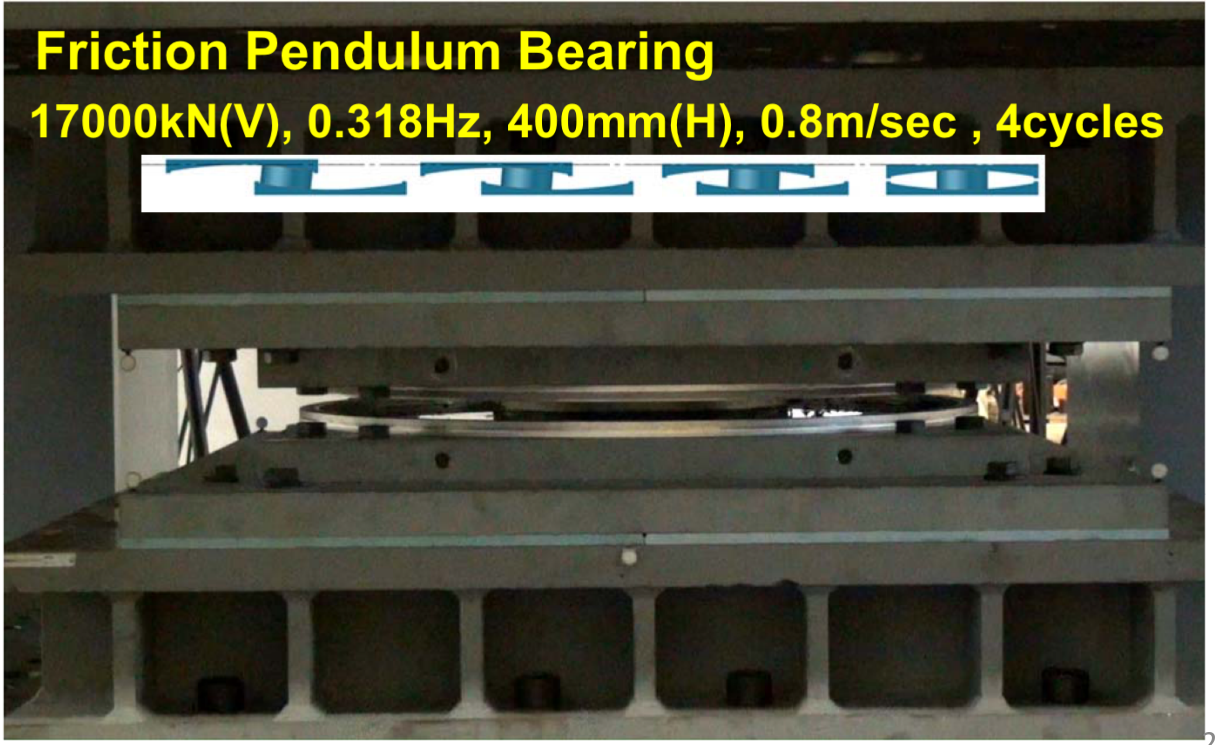


# Demonstration Test (II)



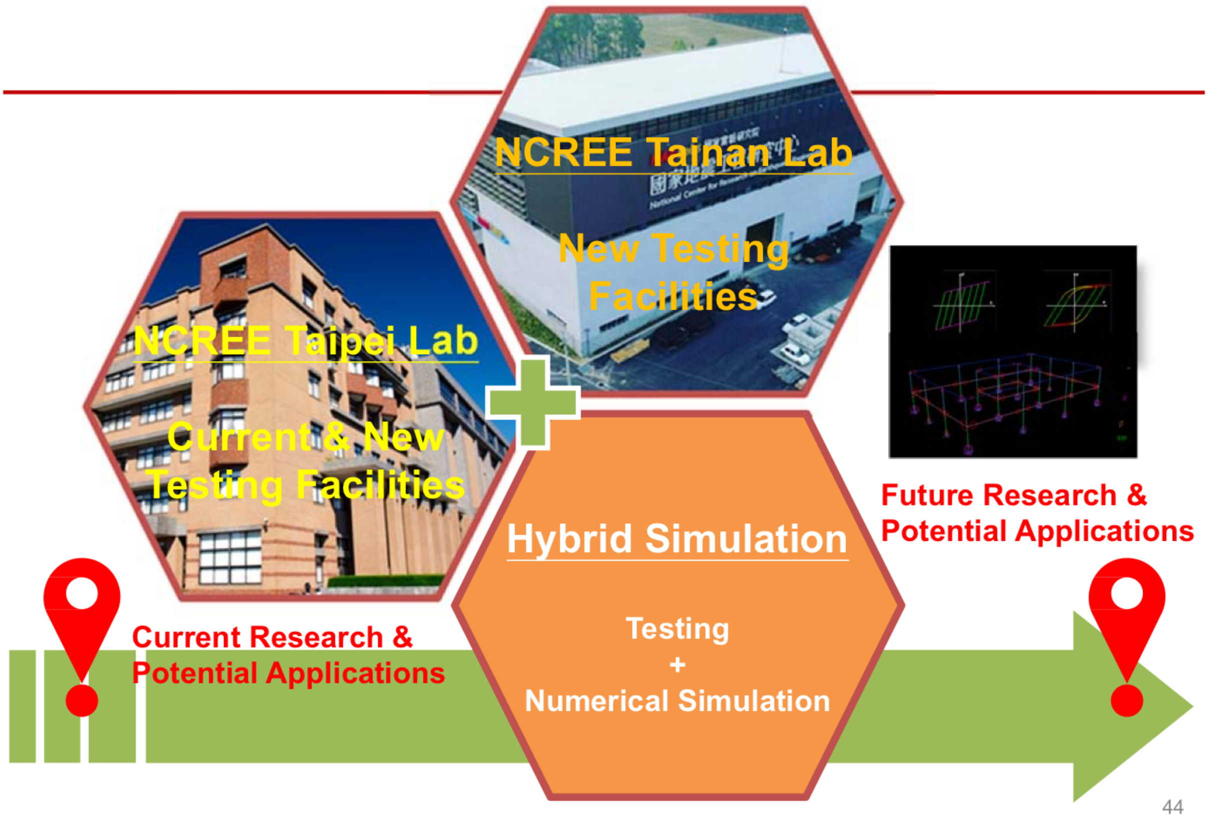
0.4Hz, 400mm, 1m/sec, 3 cycles

# Demonstration Test (III)



Friction Pendulum Bearing

17000kN(V), 0.318Hz, 400mm(H), 0.8m/sec , 4cycles



**NCREE Tainan Lab**

New Testing Facilities

**NCREE Taipei Lab**

Current & New Testing Facilities

**Hybrid Simulation**

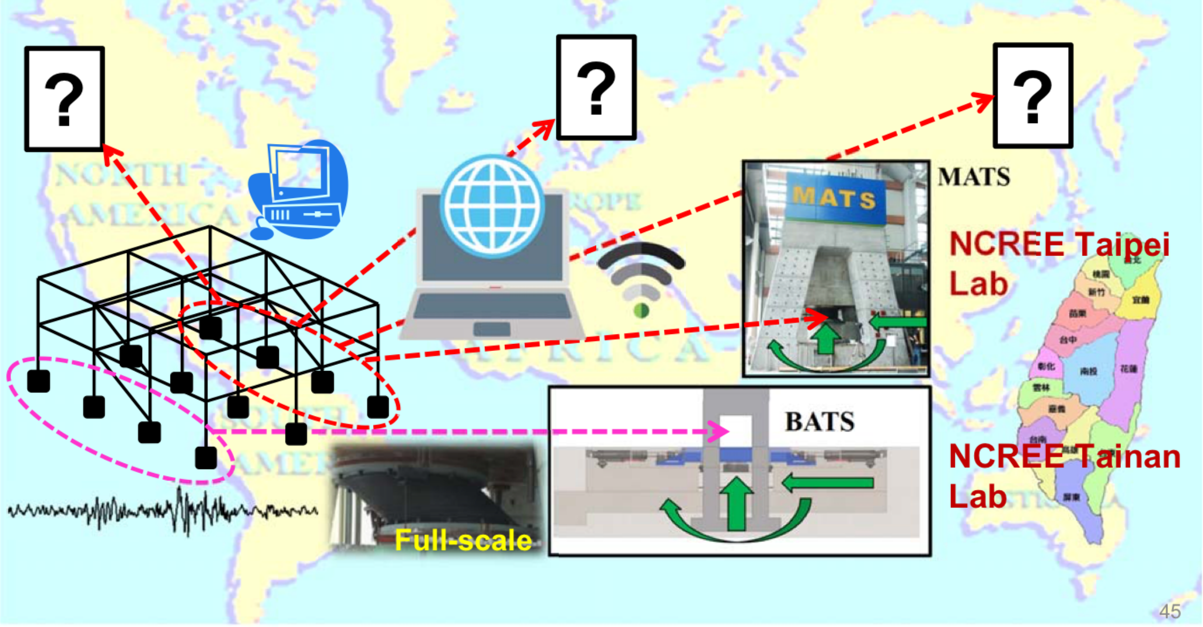
Testing
+
Numerical Simulation

Current Research & Potential Applications

Future Research & Potential Applications

# International Collaborative Test Platform

**For academia and industry**



# From Seismic Isolation to Building Mass Damper

## Dr. Kuo-Chun Chang

Professor at NTU and Consultant at NCREE

Prof. Kuo-Chun Chang is currently Distinguished Professor of the Department of Civil Engineering of National Taiwan University (NTU). Before joining the faculty of National Taiwan University in 1991, he worked as Research Assistant Professor and Associate Professor at the State University of New York at Buffalo and National Center for Earthquake Engineering Research at Buffalo for 6 years.

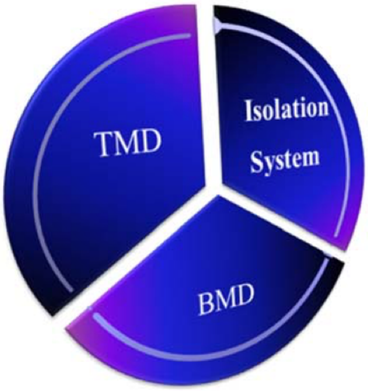
Dr. Chang served as the past Director of National Center for Research on Earthquake Engineering (NCREE) for 7 years, past department chair of civil engineering department of National Taiwan University for 6 years and the past presidents of the Chinese Structural Association and Chinese Taiwan Society of Earthquake Engineering.

Prof. Chang's research experiences relate to earthquake engineering and multiple hazards for buildings and bridges include seismic behavior and retrofit of conventional reinforced concrete structures, development of new seismic isolation and energy dissipation systems as well as structural health monitoring systems, and seismic behavior of precast segmental concrete bridge columns. In addition, he has been involved in the development of design codes and guidelines related to seismic design of buildings and bridges in Taiwan.

Experiences

- President of CTSEE
- President of CSSE
- President of TCIAE
- Chairman of Civil Engineering Department of NTU
- Distinguished Professor at NTU

# *From Seismic Isolation to Building Mass Damper*



**Kuo-Chun Chang**

***Distinguished Professor,***
***National Taiwan University***

***Shiang-Jung Wang***
***Bo-Han Lee***
***Ting-Yi Chien***
***Ying-Hsuan Chen***
***Wei-Chu Chuang***
***Shih-Pu Kuo***

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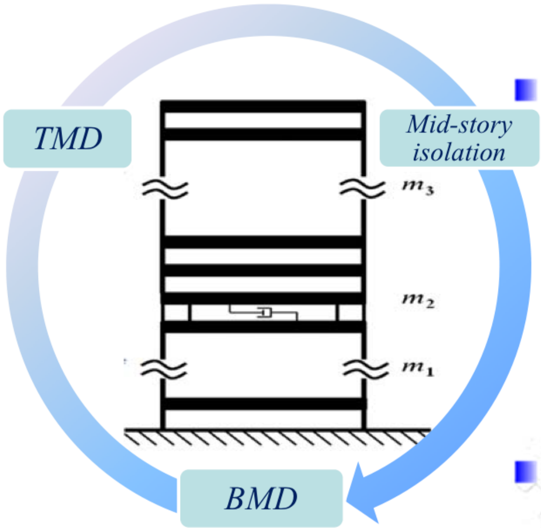
# *Outline*

## *From Seismic Isolation to Building Mass Damper – An Experimental and Numerical Study*



- ***Introduction and motivation***
- ***Analytical model and study***
- ***Experimental study***
- ***Numerical study***
- ***Concluding remarks***

# *Why to adopt mid-story isolation design*

- ***Satisfy architectural concerns of aesthetics and functionality***
- ***Enhance construction feasibility at highly populated areas***
- ***Facilitate foundation construction in site***
- ***Utilize limited available space efficiently***
- ***Drain, ventilation and regular maintenances at mid-story isolation layer become easier and more convenient***

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# *Applications of mid-story isolation design in Taiwan (1/2)*

MRT Gongguan Station

Civil Engineering Research Building of NTU

# Applications of mid-story isolation design in Taiwan (2/2)

*Story: B3F~38F*
*Height: 133.20m*
*Isolation layer: 1F*
*Isolator: 43 LRBs*
*Aspect ratio: 3.17*
*Unisolated period: 3.29sec*
*Isolated period: 5.18sec*

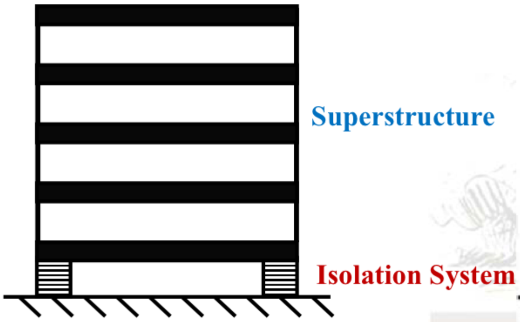
*Story: B3F~15F*
*Height: 49.95m*
*Isolation layer: 2F*
*Isolator: LRB*
*Aspect ratio: 1.49*
*Unisolated period: 1.07sec*
*Isolated period: 3.72sec*

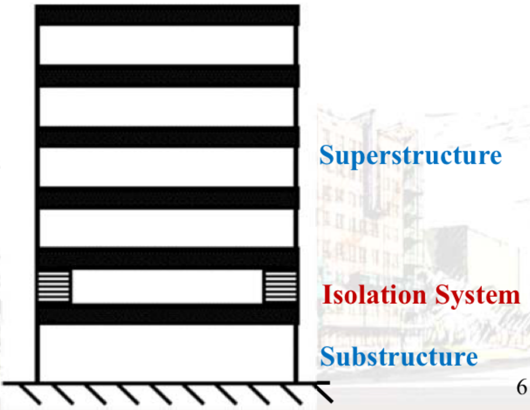
*Story: B6F~16F*
*Height: 57.80m*
*Isolation layer: 4F*
*Isolator: LRB*
*Aspect ratio: 2.36*
*Isolated period: 3.72sec*

---

# Mid-story isolation design

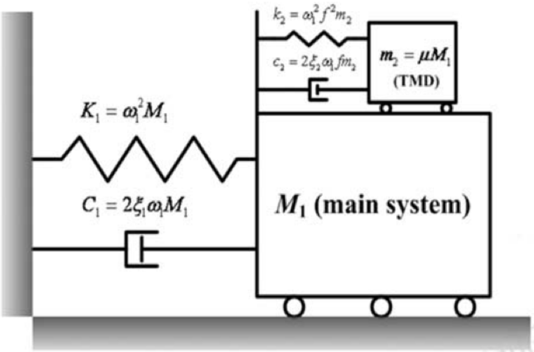
- *Major concerns for mid-story isolation design*
  - *Flexibility of substructure*
  - *Contribution of higher modes*
- *Interaction between substructure and superstructure*
- *Difference of dynamic characteristics and responses between base-isolated and mid-story isolated structures*





# *Tuned mass damper (TMD) design*

- *Consist of mass, spring, and dashpot*
- *To mitigate wind-induced responses of main structure (serviceability)*
- *Mass ratio < 10% or even much lower, in general*



**Simplified 2-Lumped-Mass Structural Model**

Mass ratio: $\mu = \dfrac{m_2}{M_1}$

$\Downarrow$

Frequency ratio: $f = \dfrac{\omega_2}{\omega_1}$

TMD damping ratio: $\xi_2 = \dfrac{c_2}{2m_2\omega_2}$

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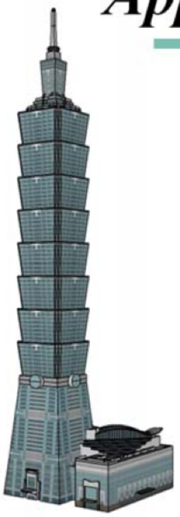
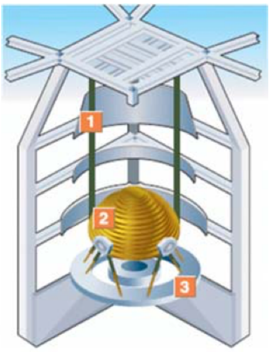
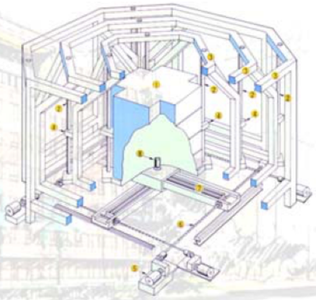
# *Applications of TMD design in Taiwan*





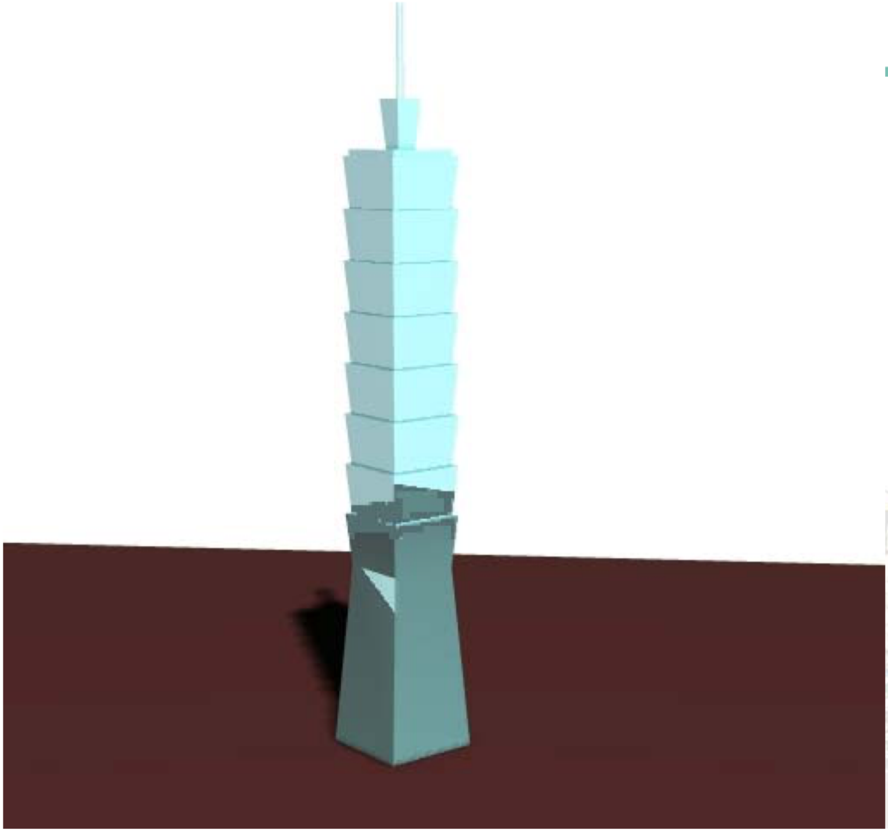
**Taipei 101 Tower**

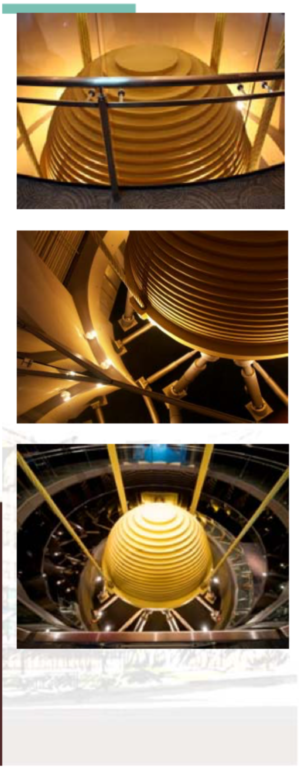
- *508m(87F~92F)*
- *The mass block weights 660 tons*
- *16 viscous damper are implemented*
- *To reduce wind-induced responses*



**KaohSiung T&C Tower**

- *378m(77F~78F)*
- *The mass block weights 80 tons*
- *Active mass damper, AMD*
- *To reduce wind-induced responses*





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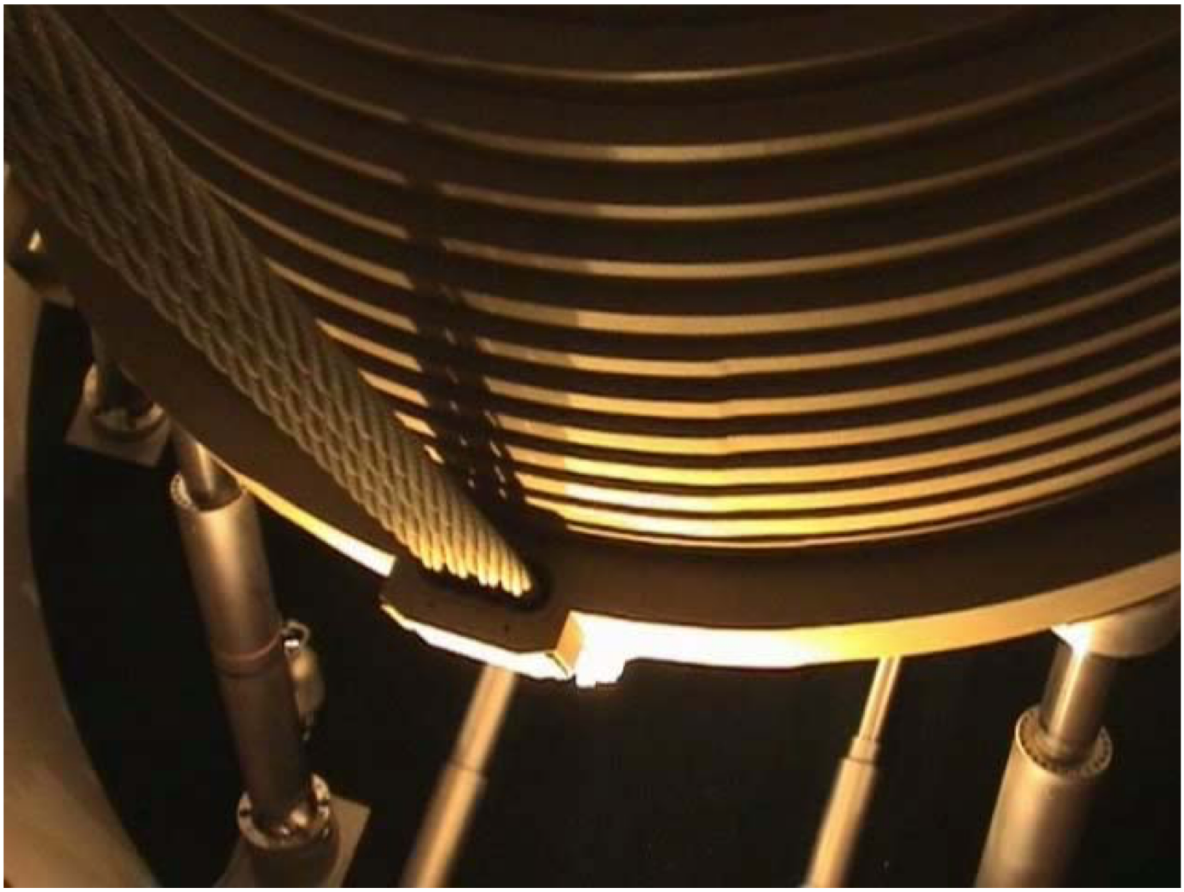
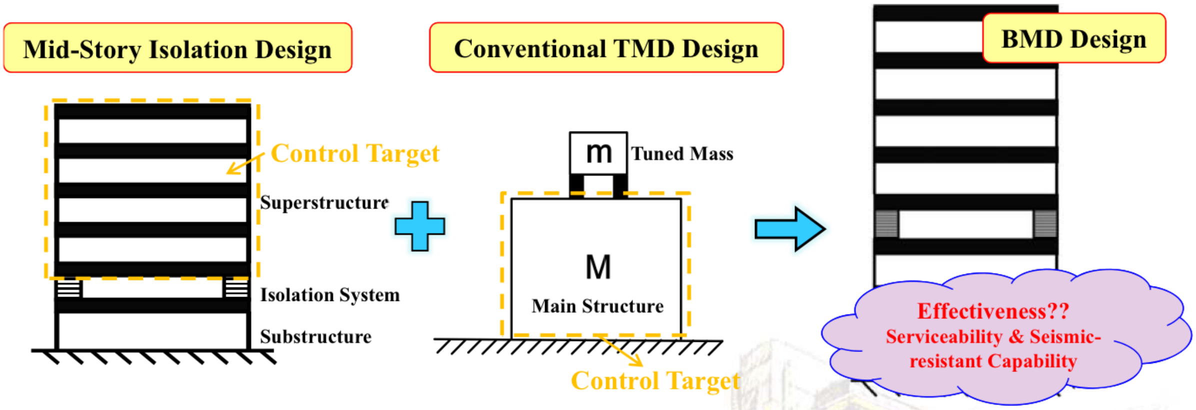


# *Motivation of study on building mass damper design (BMD)*



Effectiveness??
Serviceability & Seismic-resistant Capability

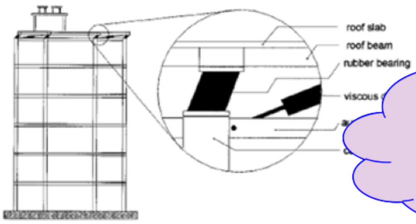
| *Response* | *Mid-story isolation design* | *TMD design* | *BMD design* |
|---|---|---|---|
| **Superstructure** | ↓ | ↑ | ↓ |
| **Substructure** | ↑ | ↓ | ↓ |

**Seismic Loading**

***Enhance both structures' performance***

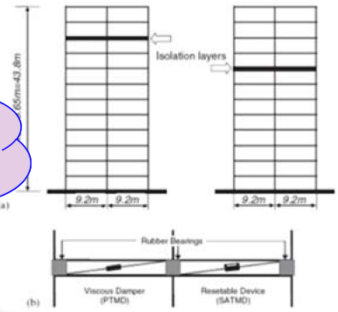
---

# *Researches regarding BMD design*

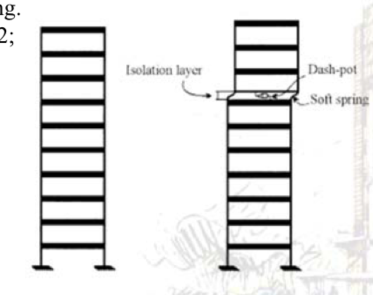


Villaverde RA. Seismic Roof Isolation System: Feasibility Study with 13-Story building. Journal of Structural Engineering, 2002; 128(2): 188-196.

**Control Target:**
**Primary Structure**
**(Substructure)**



Chey MH, Chase JG, Mander JB, and Carr AJ. Semi-active tuned mass damper building systems: Application, Earthquake Engineering and Structural Dynamics, 2010; 39(2):69–89.



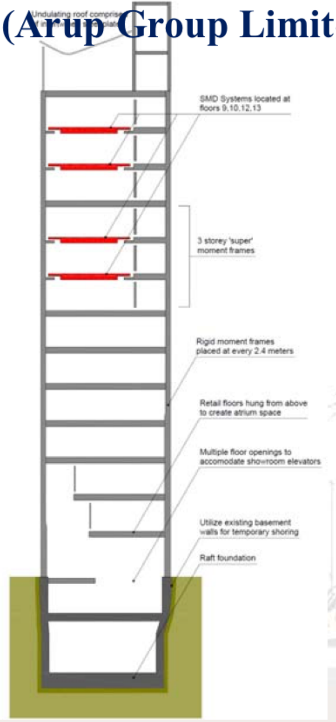
(a) - Shear building (b) - Shear building with PMI

Ziyaeifar M and Noguchit H. Partial Mass Isolation in Tall Buildings, Department of Architecture, Faculty of Engineering, Chiba University, 1-33 Yayoi-Cho, Inage-Ku, Chiba 263, Japan.

# *Limited practical applications of BMD design*

## Swatch Group Japan Headquarters in Tokyo

(Arup Group Limited)



**9F, 10F, 12F, and 13F**

**High-Damping Rubber Bearing + Sliding Bearing**

**Kidokoro R. Self mass damper (SMD): seismic control system inspired by the pendulum movement of an antique clock. *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, 2008.**

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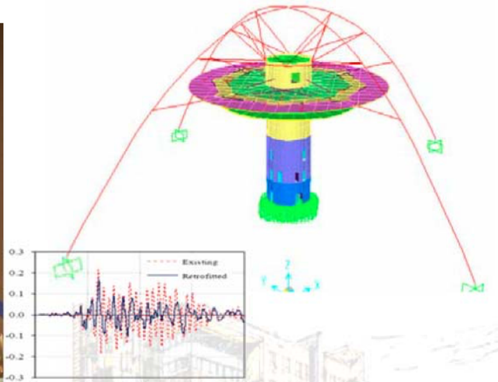
# *Limited practical applications of BMD design*

## Theme Building at Los Angeles International Airport



**Rubber Bearing + Viscous Damper**

**Amir SJ, Gilani H, Miyamoto K, Mahin S, Nighbor R. Seismic Retrofit of the LAX Theme Building with Mass Damper: Analysis and Experimentation". Proceedings of 15th World Conference on Earthquake Engineering, Lisboa, 2012.**

# *Limited practical applications of BMD design*

## Green Mass Damper

**RBs + FVDs**

**Courtesy: Prof. Kazuhiko Kasai**

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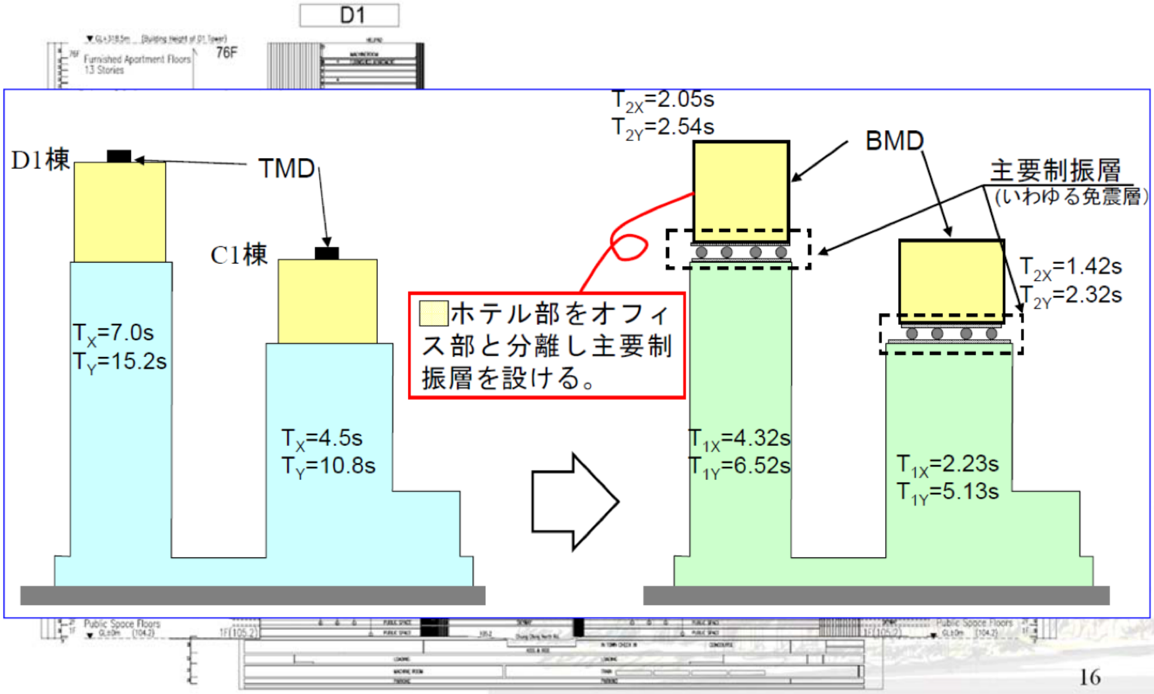
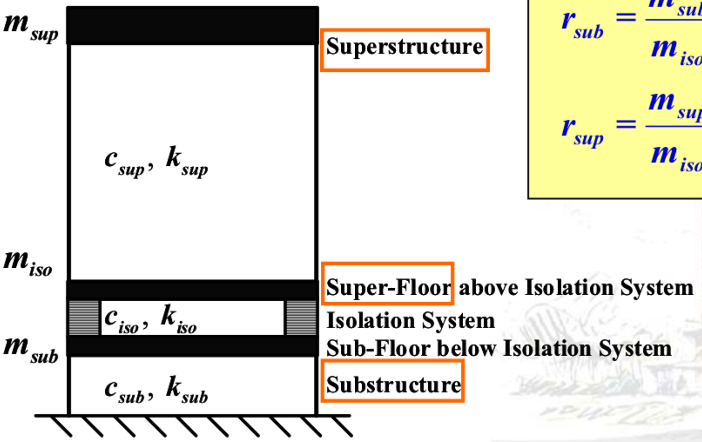
# *Preliminary design for Taipei station C1/D1*



□ホテル部をオフィス部と分離し主要制振層を設ける。

# *Simplified 3-lumped-mass structural model*

- ***Equivalent Linear Analysis***
  - ***All structural elements except isolation system remain elastic***
  - ***Isolation System → Equivalent Linear Model***



**Mass Ratio**

$$r_{sub} = \frac{m_{sub}}{m_{iso}}$$

$$r_{sup} = \frac{m_{sup}}{m_{iso}}$$

**Nominal Frequency**

$$\omega_{sup} = \sqrt{\frac{k_{sup}}{m_{sup}}}$$

$$\omega_{iso} = \sqrt{\frac{k_{iso}}{m_{iso} + m_{sup}}}$$

$$\omega_{sub} = \sqrt{\frac{k_{sub}}{m_{sub}}}$$

**Component Damping**

$$\xi_{iso} = \frac{c_{iso}}{2\omega_{iso}(m_{iso} + m_{sup})}$$

---

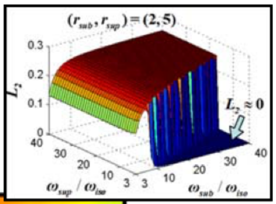
# *Fundamental and higher modal characteristics*

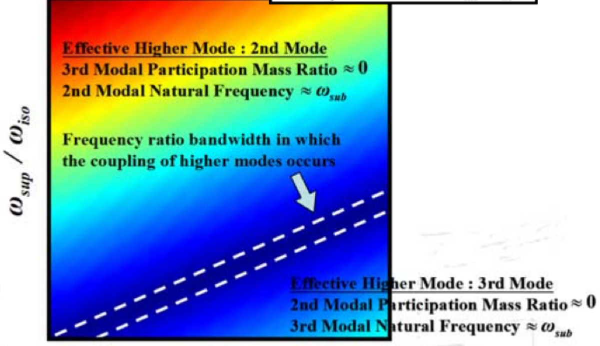
***First Modal Damping Ratio***

$$\xi_1 = \frac{\xi_{iso}}{\left(1 + \frac{2(1+r_{sup})}{r_{sub}}\left(\frac{\omega_{iso}}{\omega_{sub}}\right)^2 + \frac{2r_{sup}}{1+r_{sup}}\left(\frac{\omega_{iso}}{\omega_{sup}}\right)^2\right)}$$

***First Modal Participation Mass Ratio***

$$L_1 = \frac{r_{sub} + 2(r_{sub} + r_{sup} + 1)\left(\frac{\omega_{iso}}{\omega_{sub}}\right)^2 + \frac{2r_{sub}r_{sup}}{1+r_{sup}}\left(\frac{\omega_{iso}}{\omega_{sup}}\right)^2}{(1 + r_{sub} + r_{sup})\left(\frac{r_{sub}}{1+r_{sup}} + 2\left(\frac{\omega_{iso}}{\omega_{sub}}\right)^2 + \frac{2r_{sub}r_{sup}}{(1+r_{sup})^2}\left(\frac{\omega_{iso}}{\omega_{sup}}\right)^2\right)}$$

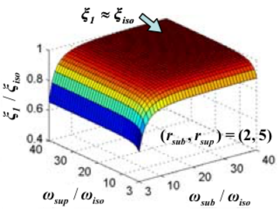


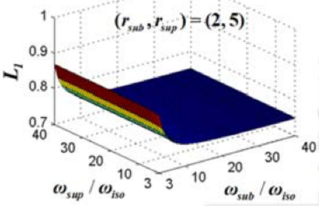


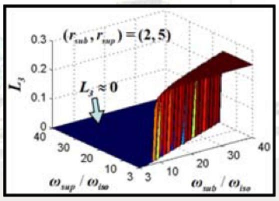
**Effective Higher Mode : 2nd Mode**
3rd Modal Participation Mass Ratio $\approx 0$
2nd Modal Natural Frequency $\approx \omega_{sub}$

Frequency ratio bandwidth in which the coupling of higher modes occurs

**Effective Higher Mode : 3rd Mode**
2nd Modal Participation Mass Ratio $\approx 0$
3rd Modal Natural Frequency $\approx \omega_{sub}$

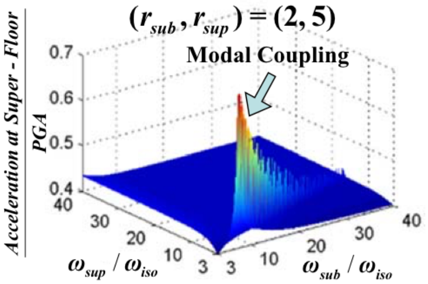




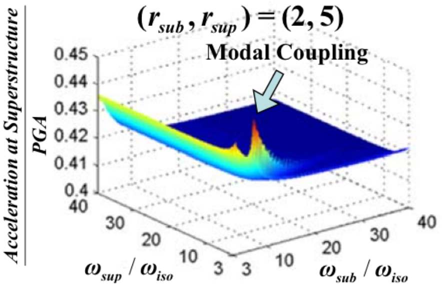


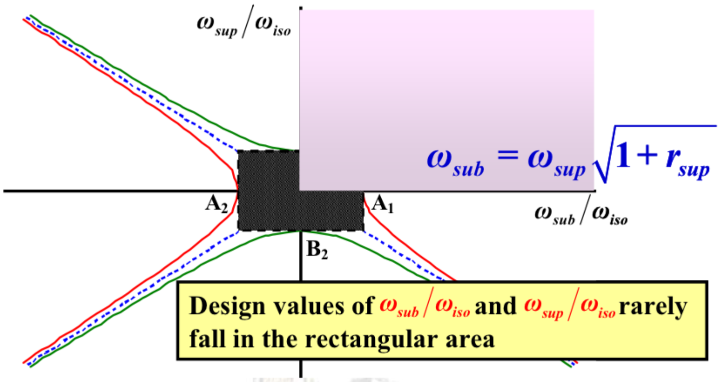
# *Adverse effect arising from coupling of higher modes due to improper design*

*Maximum acceleration responses at super-floor*



*Maximum acceleration responses at superstructure*





$$\omega_{sub} = \omega_{sup}\sqrt{1 + r_{sup}}$$

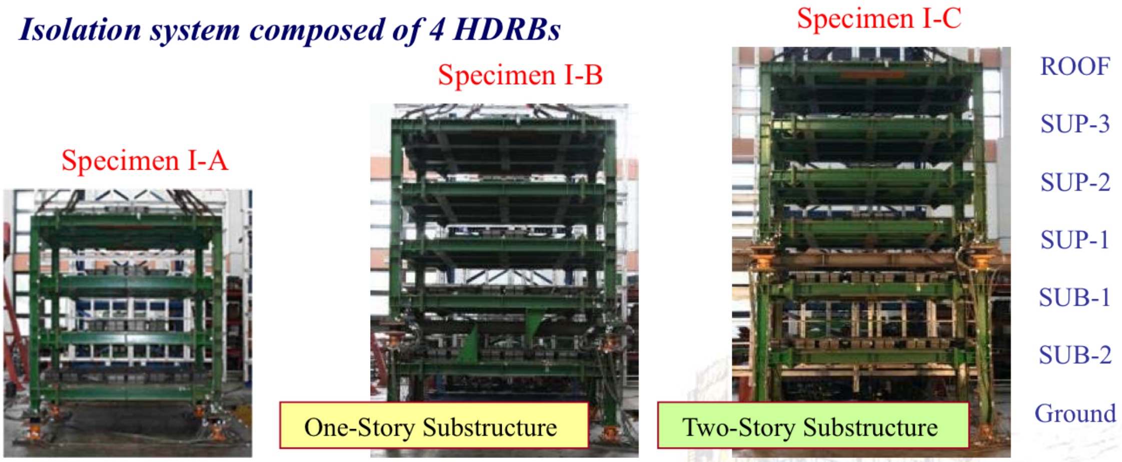
**Design values of $\omega_{sub} / \omega_{iso}$ and $\omega_{sup} / \omega_{iso}$ rarely fall in the rectangular area**

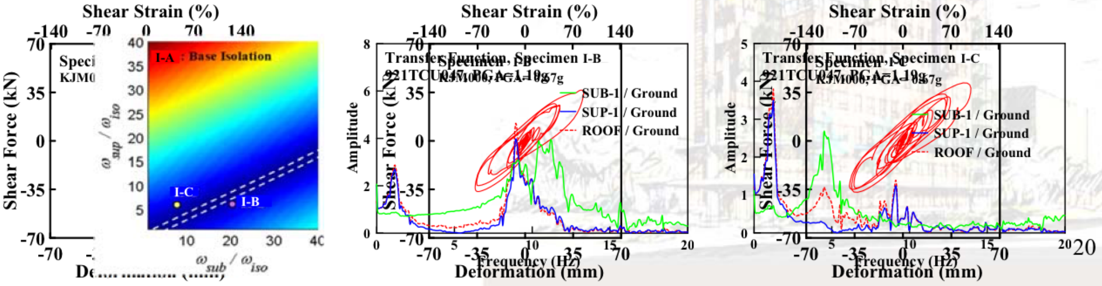
- *Capable of accurately predicting the bandwidth*
- *Linear function*
- *Independent of* $\omega_{iso}$ →
  - *Different types and mechanical properties of seismic isolation bearings*
  - *Different deformation extent (linear or nonlinear) of seismic isolation bearings*

---

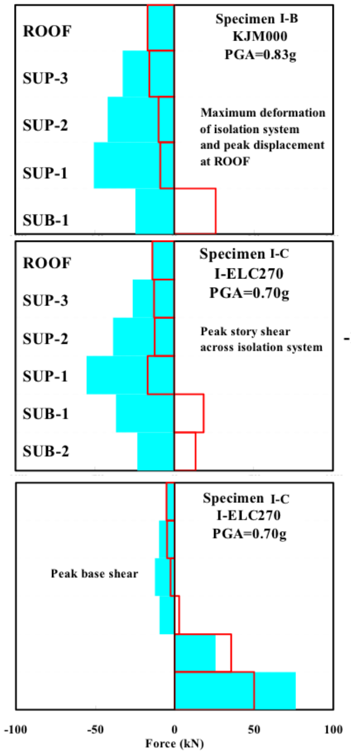
# *Test 1: to discuss discrepancies between base-isolated and mid-story isolated buildings*

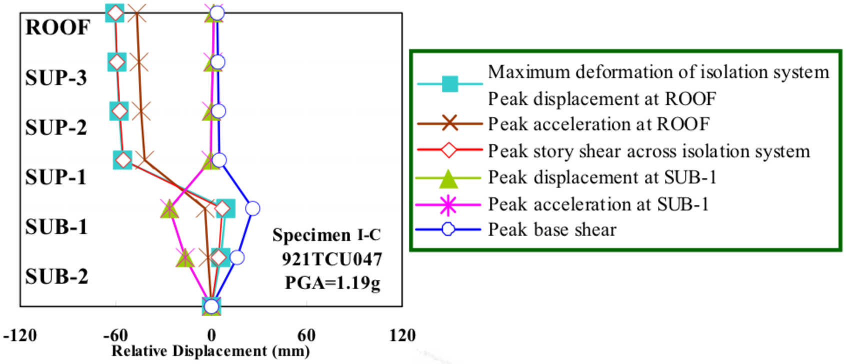
*Isolation system composed of 4 HDRBs*





# *Vertical distributions of inertia force, story shear force and displacement responses*





- ***A phase lag of larger than 90 degrees between seismic responses acting at substructure and superstructure when peak seismic responses occur at isolation system and superstructure***
- ***Inertia force responses acting at substructure due to higher mode responses contributes significantly to base shear force responses***

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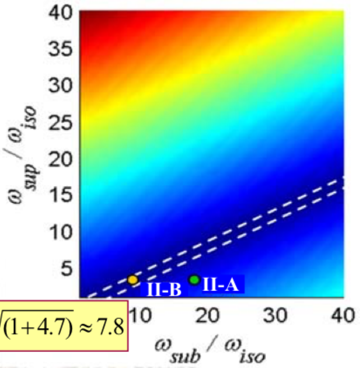
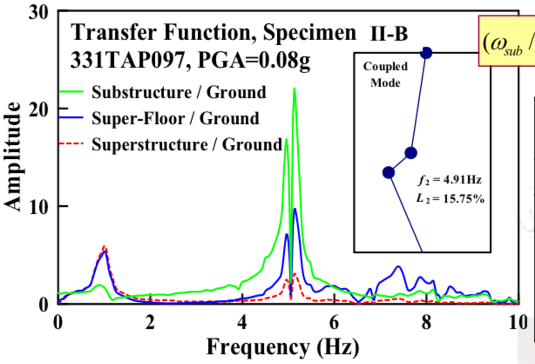
# *Test 2: to demonstrate adverse effect arising from coupling of higher modes*

- ***3-story steel frame: substructure, super-floor, and superstructure***
- ***Isolation system composed of 4 LRBs***



$$(\omega_{sub}/\omega_{iso}) = (\omega_{sup}/\omega_{iso})\sqrt{1+r_{sup}} = 3.3\sqrt{(1+4.7)} \approx 7.8$$



| Input Excitation | | 331<br>TAP097 | | 921<br>NCREE | | 331TAP097<br>code | |
|---|---|---|---|---|---|---|---|
| Test PGA (g) | | 0.32 | | 0.32 | | 0.32 | |
| Test Specimen | | II-A | II-B | II-A | II-B | II-A | II-B |
| Ratio of Peak Acceleration Response to PGA | Substructure | 1.05 | 2.43 | 1.34 | 2.58 | 2.41 | 2.41 |
| | Super-Floor | 0.62 | 1.02 | 0.85 | 1.03 | **1.28** | **1.77** |
| | Superstructure | 0.41 | 0.60 | 0.65 | 0.77 | 0.72 | 0.86 |

# Simplified 3-lumped-mass structural model

- ***Mass ratio***

$$\mu_2 = \frac{m_2}{m_1}, \quad \mu_3 = \frac{m_3}{m_1}$$

- ***Component damping***

$$\xi_1 = \frac{c_1}{2(m_1 + m_2 + m_3)\omega_1} \quad \xi_2 = \frac{c_2}{2(m_2 + m_3)\omega_2} \quad \xi_3 = \frac{c_3}{2m_3\omega_3}$$

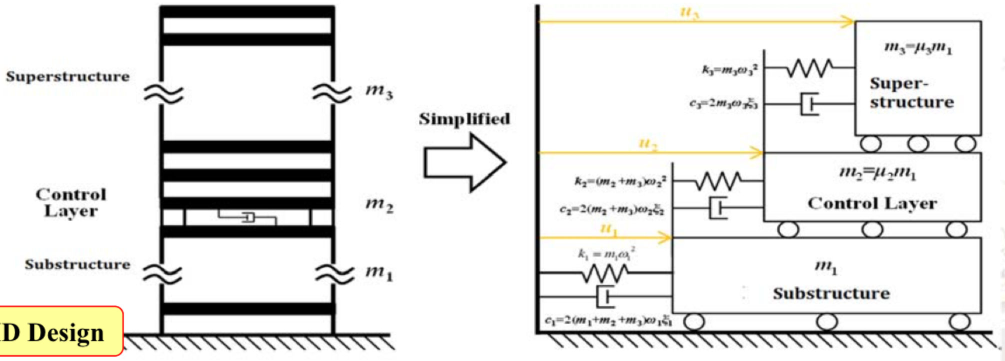
- ***Frequency ratio***

$$f_2 = \frac{\omega_2}{\omega_1}, f_3 = \frac{\omega_3}{\omega_1} \qquad \omega_1 = \sqrt{\frac{k_1}{m_1}} \quad \omega_2 = \sqrt{\frac{k_2}{m_2 + m_3}} \quad \omega_3 = \sqrt{\frac{k_3}{m_3}}$$

**Parametric analysis**

Modal characteristic control

Dynamic response control



**BMD Design**

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# Modal characteristic control (1/2)

- ***Refer to Sadek's method (1997)***
- ***BMD system parameters:*** $\mu_2, \mu_3, f_2, f_3, \xi_1, \xi_2, \xi_3$

**Parametric analysis**

Modal characteristic control

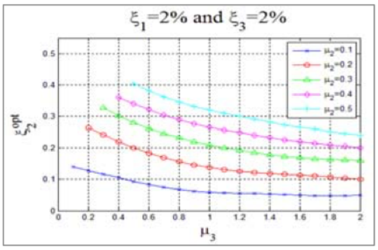
Dynamic response control

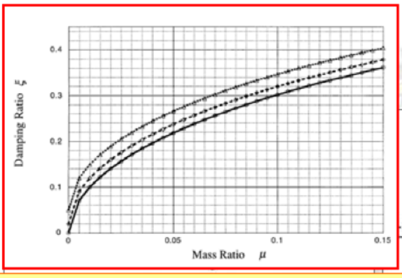
Complex eigenvalues of equation of motion

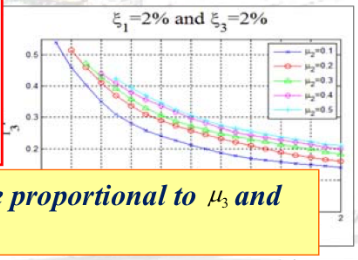
$$\lambda'_{2n-1,2n} = \omega'_n\xi'_n \pm i\omega'_n\sqrt{1-\xi'^2_n}, n = 1, 2, 3$$

**Modal Characteristic** $\omega'_1 \cong \omega'_3 \cong \omega'_5$ $\xi'_1 \cong \xi'_3 \cong \xi'_5$

**OBMD**



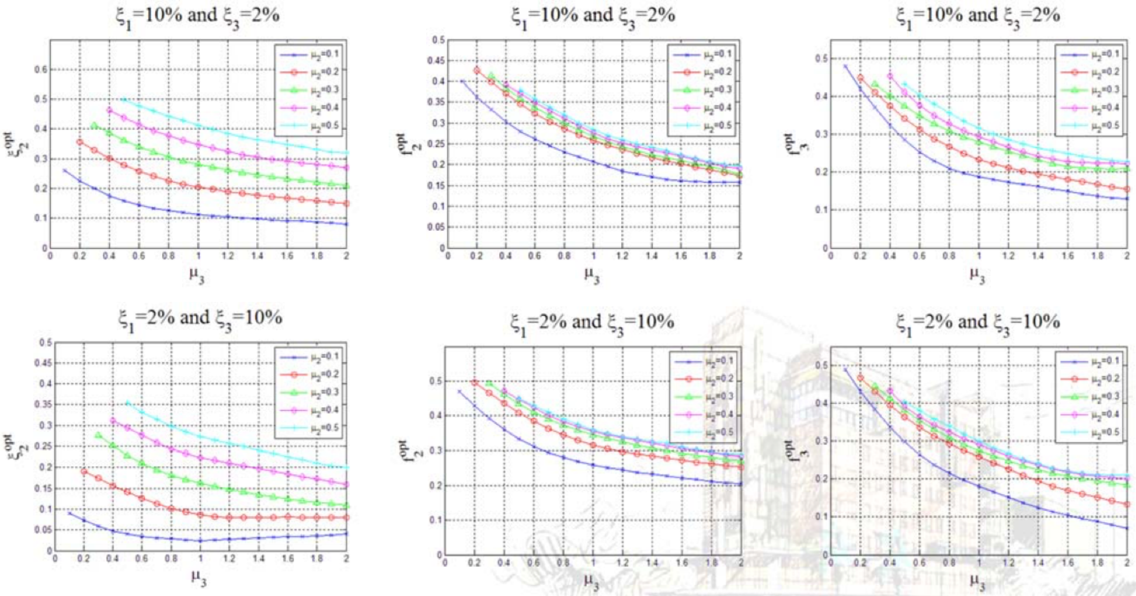




- ***Optimum design parameters*** $\xi_2^{opt}$, $f_2^{opt}$, *and* $f_3^{opt}$ ***in general are proportional to*** $\mu_3$ ***and are non-proportional to*** $\mu_2$

Sadek F, Mohraz B, Taylor AW and Chung RM. A Method of Estimating The Parameters of Tuned Mass Dampers for Seismic Applications. Earthquake Engineering and Structural Dynamics, 1997; 26: 617-635.

# *Modal characteristic control (2/2)*



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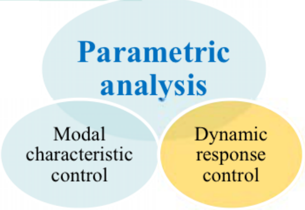
# *Dynamic response control*

- ***Refer to Tsai's method (1993)***
- ***Fixed acceleration amplitude support excitation***

$$\mathbf{M\ddot{u}} + \mathbf{C\dot{u}} + \mathbf{Ku} = \mathbf{MR}\ddot{u}_g \qquad \ddot{u}_g = Ge^{i\omega t}$$

- ***Vibration amplitude of each DOF to input amplitude***

$$\frac{\omega_1^2|u_1|}{G}, \frac{\omega_1^2|u_2|}{G}, \frac{\omega_1^2|u_3|}{G}$$



**Parametric analysis**

Modal characteristic control

Dynamic response control

$$Objective\ function = Min.\left(\frac{\omega_1^2|u_1|}{G} + \frac{\omega_1^2|u_2|}{G} + \frac{\omega_1^2|u_3|}{G}\right)$$

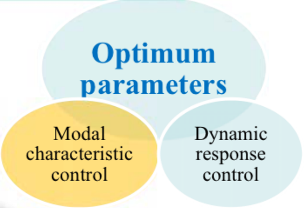
Obtain $f_2^{opt}$, $\xi_2^{opt}$, $f_3^{opt}$

**OBMD**

Tsai HC and Lin GC. Optimum Tuned-Mass Dampers for Minimizing Steady-State Response of Support-Excited and Damped Systems. Earthquake Engineering and Structural Dynamics, 1993; 23: 957-973.

# *Test specimens*

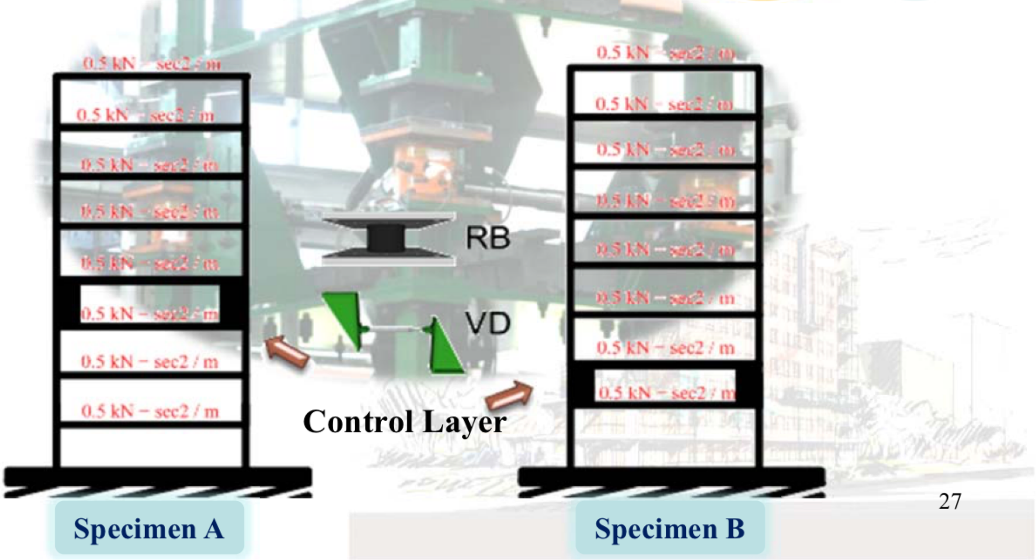
- ***Different levels of control layers***
  - *Specimen A : 3(Substructure)+4(Superstructure)*
  - *Specimen B : 1(Substructure)+6(Superstructure)*



**Optimum parameters**

Modal characteristic control

Dynamic response control



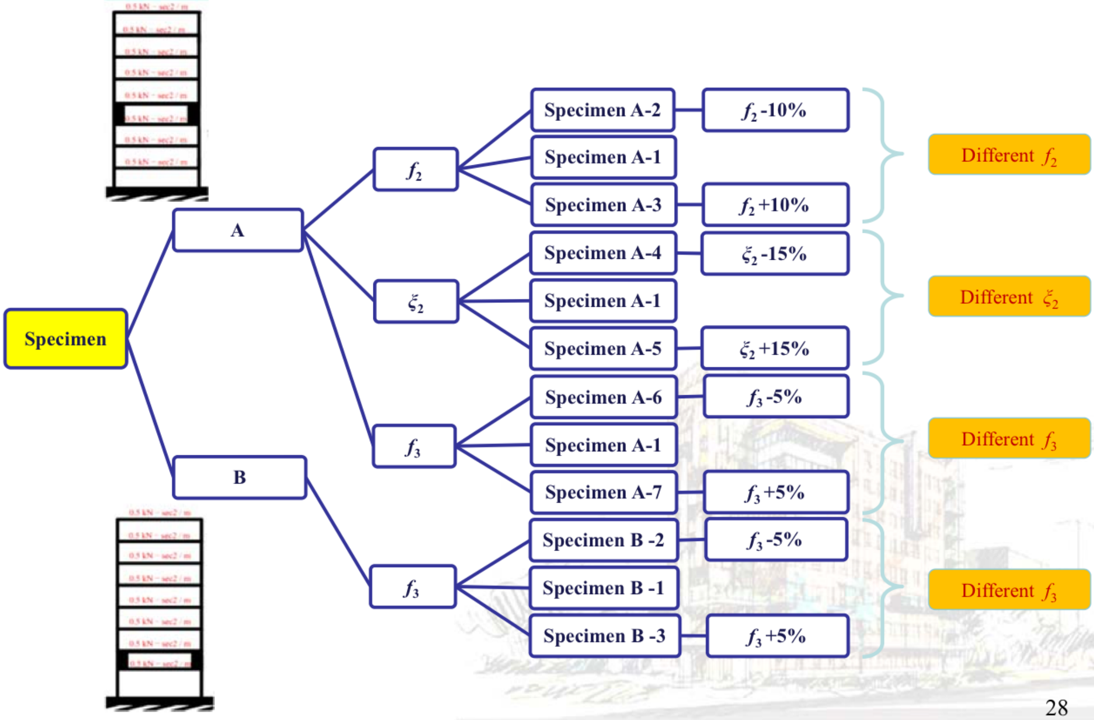
**Control Layer**

**Specimen A**

**Specimen B**

---

# *Design parameters*



**Specimen**

- **A**
  - $f_2$
    - **Specimen A-2** — $f_2$-10%
    - **Specimen A-1**
    - **Specimen A-3** — $f_2$+10%
  - $\xi_2$
    - **Specimen A-4** — $\xi_2$-15%
    - **Specimen A-1**
    - **Specimen A-5** — $\xi_2$+15%
  - $f_3$
    - **Specimen A-6** — $f_3$-5%
    - **Specimen A-1**
    - **Specimen A-7** — $f_3$+5%
- **B**
  - $f_3$
    - **Specimen B -2** — $f_3$-5%
    - **Specimen B -1**
    - **Specimen B -3** — $f_3$+5%

Different $f_2$

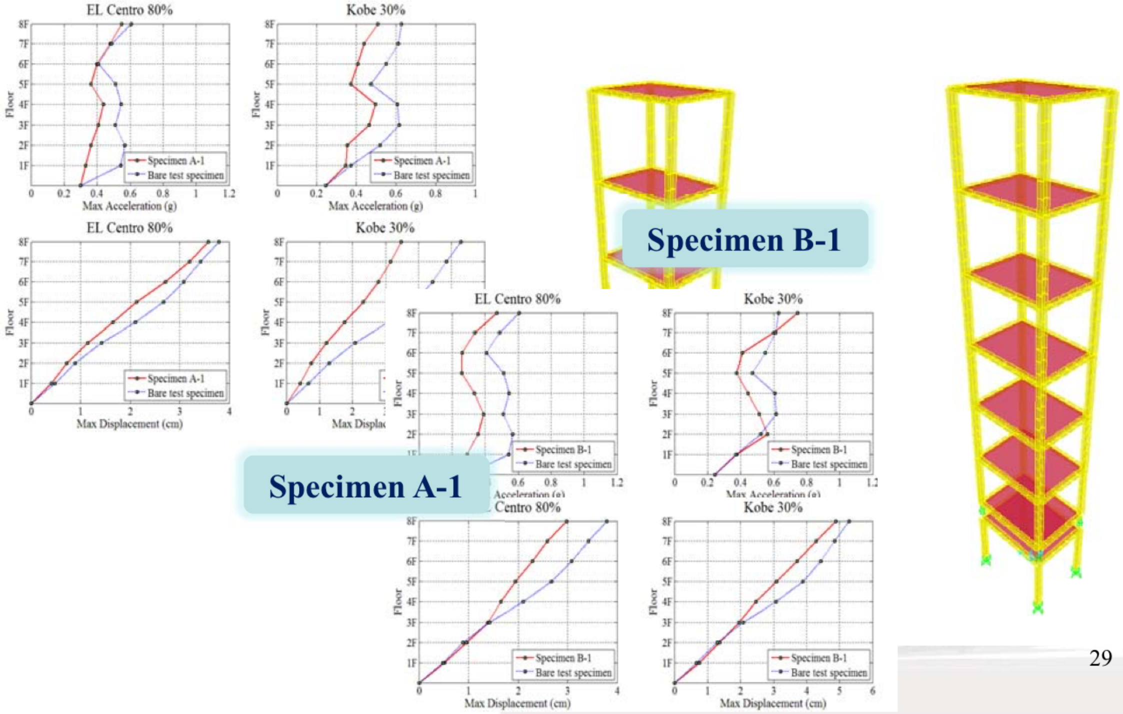
Different $\xi_2$

Different $f_3$

Different $f_3$

# *Response of specimens with and without BMD design*

**Comparison of Bare Test Frame and Specimen A-1, B-1**



**Specimen B-1**

**Specimen A-1**

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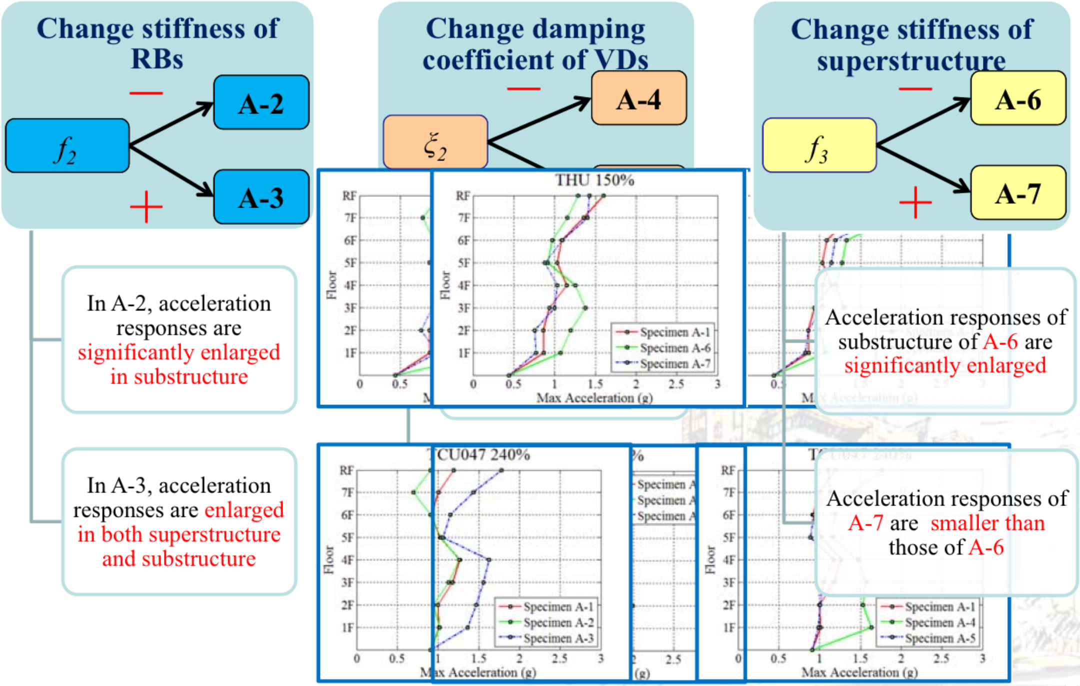
# *Sensitivity analyses on varied design parameters for BMD design*



**Change stiffness of RBs**

**Change damping coefficient of VDs**

**Change stiffness of superstructure**

In A-2, acceleration responses are significantly enlarged in substructure

In A-3, acceleration responses are enlarged in both superstructure and substructure

Acceleration responses of substructure of A-6 are significantly enlarged

Acceleration responses of A-7 are smaller than those of A-6

# *Effectiveness of OBMD design in reducing seismic responses*

- ***OBMD model***
  - ***3(Substructure)+4(Superstructure)***

*System identification*

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*Numerical model*

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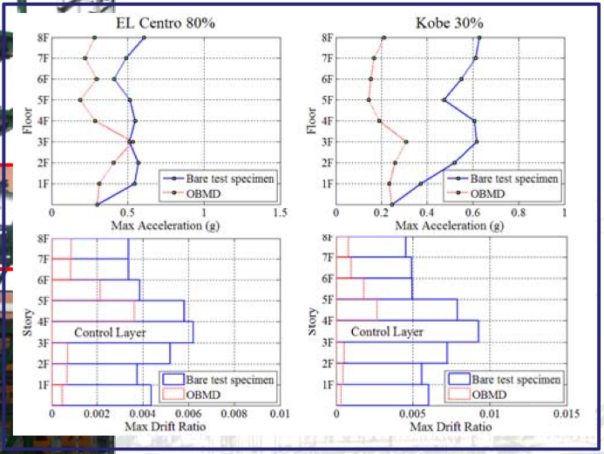
$\xi_{2,opt}$ 、$f_{2,opt}$ 、$f_{3,opt}$
*of test specimen*



**OBMD design may effectively enhance seismic performance**

**Optimum parameters**

Modal characteristic control

Dynamic response control

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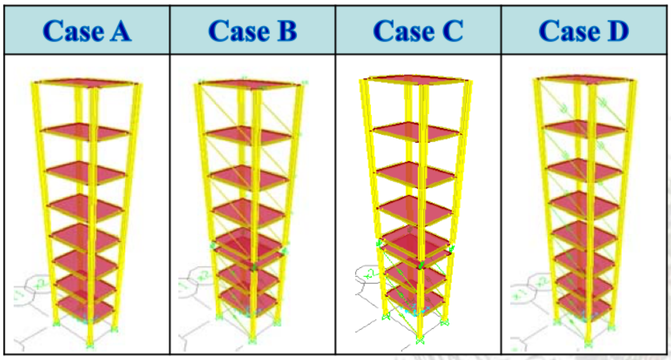
# *Numerical models*

| Model | Type | Optimum parameters | | | Design assumption | |
|---|---|---|---|---|---|---|
| | | $f_2$ | $f_3$ | $\xi_2$ | $\xi_1$ | $\xi_3$ |
| Case A | Bare frame | - | - | - | - | - |
| Case B | OBMD design | 0.95 | 1.40 | 0.19 | 0.08 | 0.02 |
| Case C | Mid-story isolation design | - | - | 0.19 | 0.08 | 0.02 |
| Case D | Energy dissipation design with VDs | - | - | - | 0.08 | |

**Optimum parameters**

Modal characteristic control

Dynamic response control



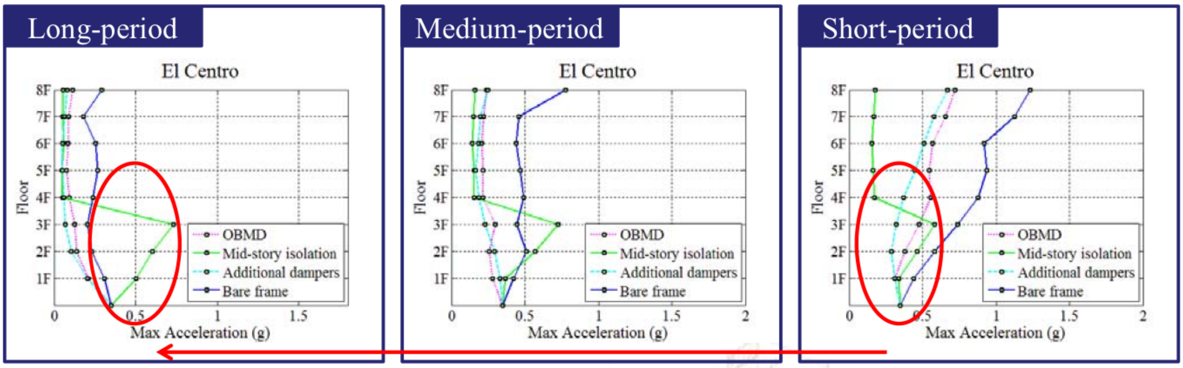
**Short-period case**

**Numerical models (A, B, C, D)**

**Long-period case**

**Medium-period case**

# *Numerical comparison between models with different vibration periods*



- **When increasing the vibration period of the bare frame model and adopting mid-story isolation design, the substructure's acceleration might be greatly enlarged**
- **OBMD design may reduce acceleration of both superstructure and substructure effectively, especially for a bare frame model with longer vibration period**

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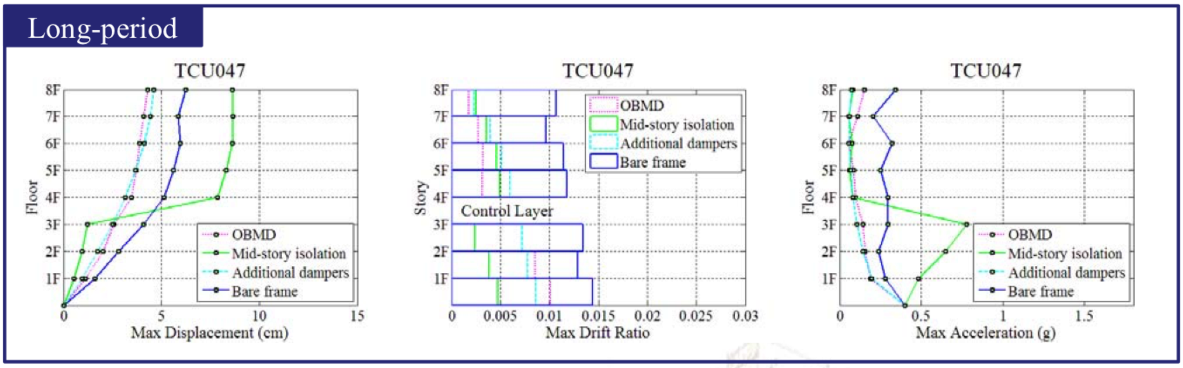
# *Responses of long-period model*



- **In long-period case, mid-story isolation design may reduce drift ratio effectively, but substructure's acceleration response might be enlarged**
- **Compared with mid-story isolation design, OBMD design may reduce seismic responses more effectively in long-period case**
- **OBMD design almost has the same response reduction as energy dissipation design**

# *Concluding remarks*

- In mid-story isolation design, higher mode responses contribute significantly to force responses at substructure
- Coupling of higher modes results in enlarged acceleration responses at super-floor and superstructure
- A new structural design concept, optimum building mass damper (OBMD), is studied to combine advantages of tuned mass damper (TMD) and mid-story isolation
- Compared with traditional TMD system, OBMD design can utilize space more effectively and economically
- Preliminary numerical and experimental comparison results disclose that the proposed OBMD design method is practicable and effective to seismically protect both substructure and superstructure, especially for long-period (high-rise) buildings

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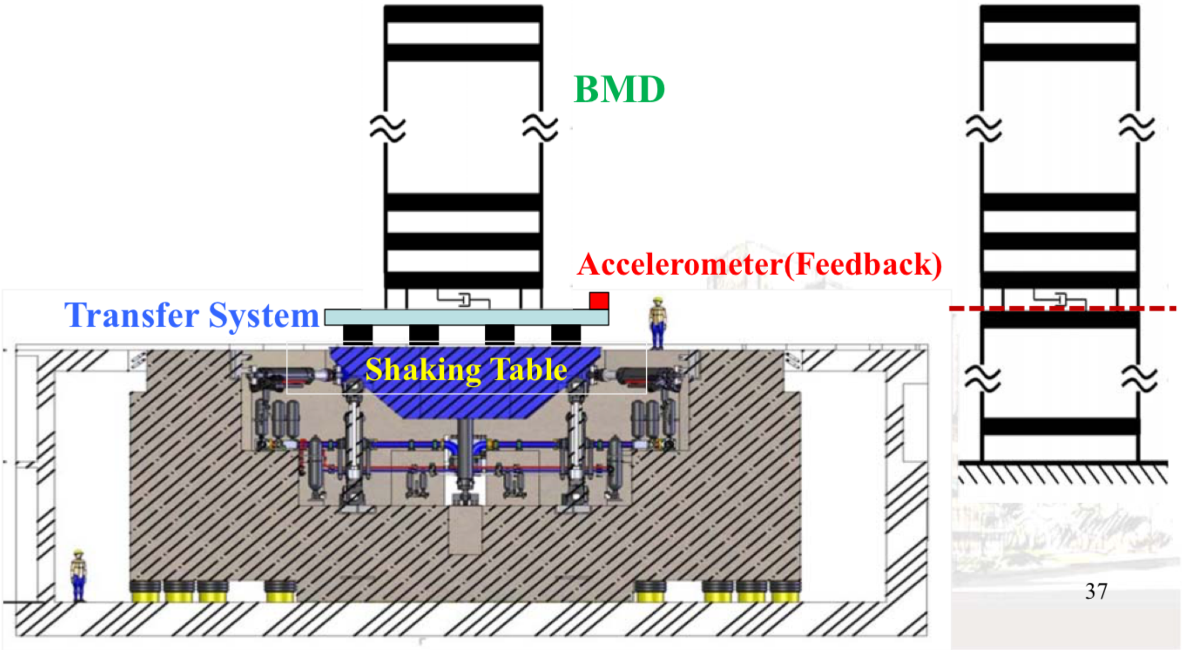
# *Future work (1/2)*

- A series of shaking table tests will be performed to further verify the effectiveness of the proposed OBMD design method based on the dynamic response control concept
- Semi-active or active control devices will be applied to OBMD design to further enhance its control performance
- The effectiveness of OBMD design under near fault ground motions will be further studied

# *Future work (2/2)*

## Hybrid Simulation



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# *Thank you for your attention*