Auckland Structural Group, New Zealand, May 2, 2017

State of the Art of Tall and Super-tall Building Structures in China

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Faculty and Facility


Prof. Jun SUN


Prof. Haifan XIANG

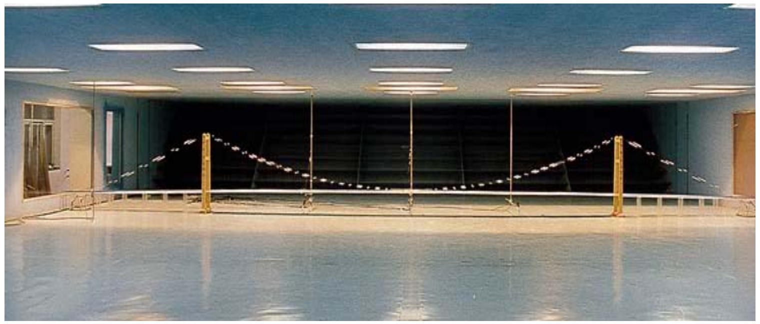

Prof. Yaoru LU


Prof. Zuyan SHEN

4 Academician + 300 Faculty+100 Staff


Shaking table array


Heavy compressor


Wind Tunnel

Faculty and Facility

College

- Department of Building Engineering
- Department of Geotechnical Engineering
- Department of Bridge Engineering
- Department of Hydraulic Engineering
- Research Institute of Structural Engineering and Disaster Reduction (42 faculty+18 Staff)

- State Key Laboratory of Disaster Reduction in Civil Engineering
- International Joint Research Laboratory of Earthquake Engineering (ILEE)

1. Background of Tall Buildings

1. Background of Tall Buildings

Super-tall Buildings in China

Ping An Finance Center (660 m)	Shanghai Center Tower (632 m)	Wuhan Greenland Center (606 m)	Goldin Finance 117 (597 m)	Z15 Tower (528 m)
$PGA_{10\%/50y}$=0.1g	$PGA_{10\%/50y}$=0.1g	$PGA_{10\%/50y}$=0.05g	$PGA_{10\%/50y}$=0.1g	$PGA_{10\%/50y}$=0.2g
Shenzhen	**Shanghai**	**Wuhan**	**Tianjin**	**Beijing**

1. Background of Tall Buildings

Before 1976 Tangshan earthquake

1. Background of Tall Buildings

After 1976 Tangshan earthquake (M=7.6)

1. Background of Tall Buildings

1. Background of Tall Buildings

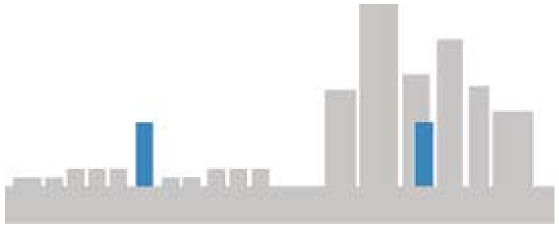
1.1 Definition of Tall Buildings

Tall buildings exhibit some characteristics as below :

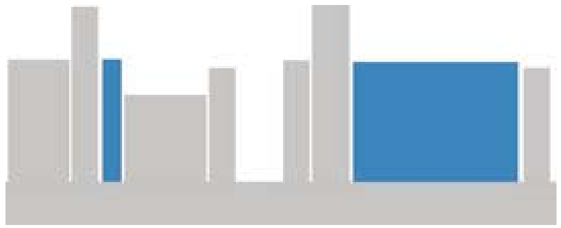
- Height relative to context
- Proportion
- Tall building technologies

Definition of tall buildings in different countries

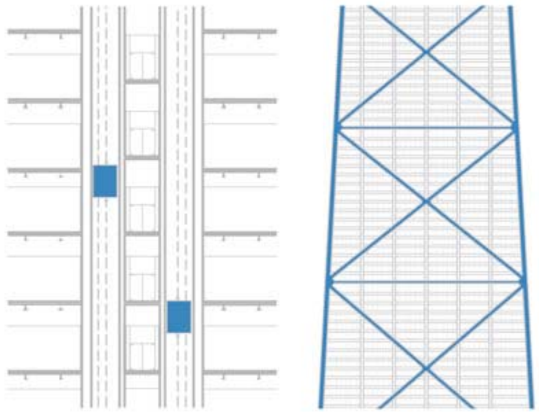
Countries	Height	stories
China	>28m for residential buildings >24m for other civil buildings	≥10 floors
Japan	>31m for civil buildings	>8 floors
USA	>24.6m for civil buildings	>7 floors
UK	>24.3m for civil buildings	—



Height relative to context



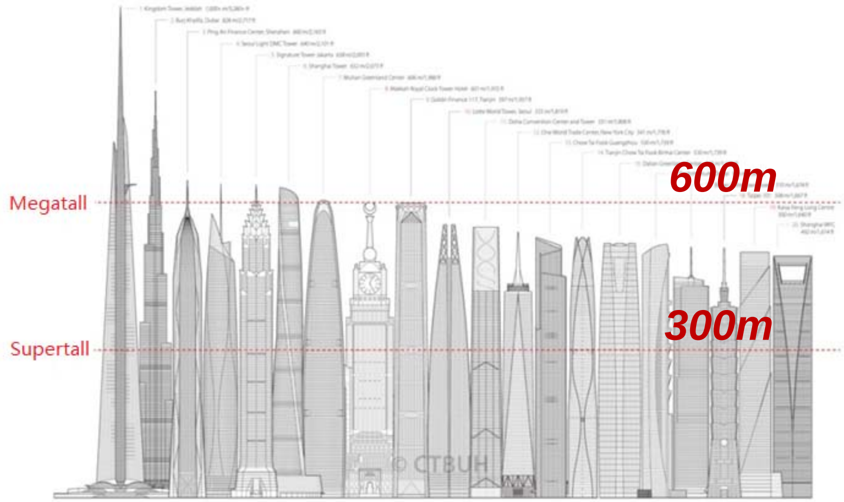
Proportion



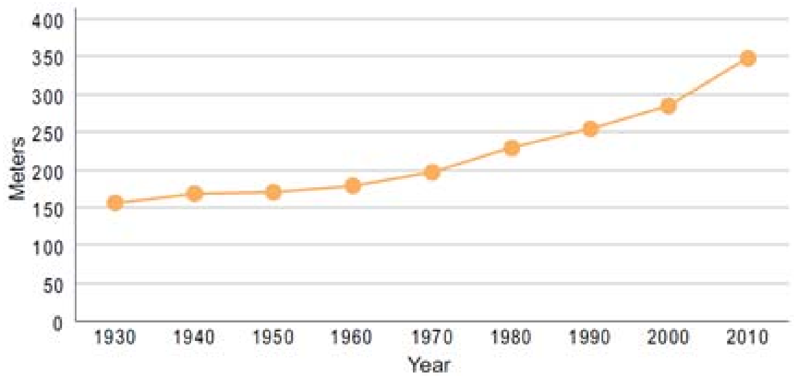
Tall building technologies

1. Background of Super-tall Buildings

1.2 Development of Tall Buildings

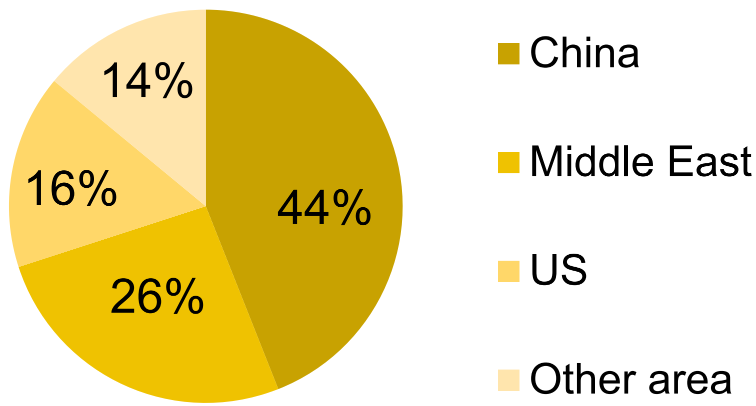


World's 20 Tallest in 2020



Average Height of the 100 Tallest Buildings in the World

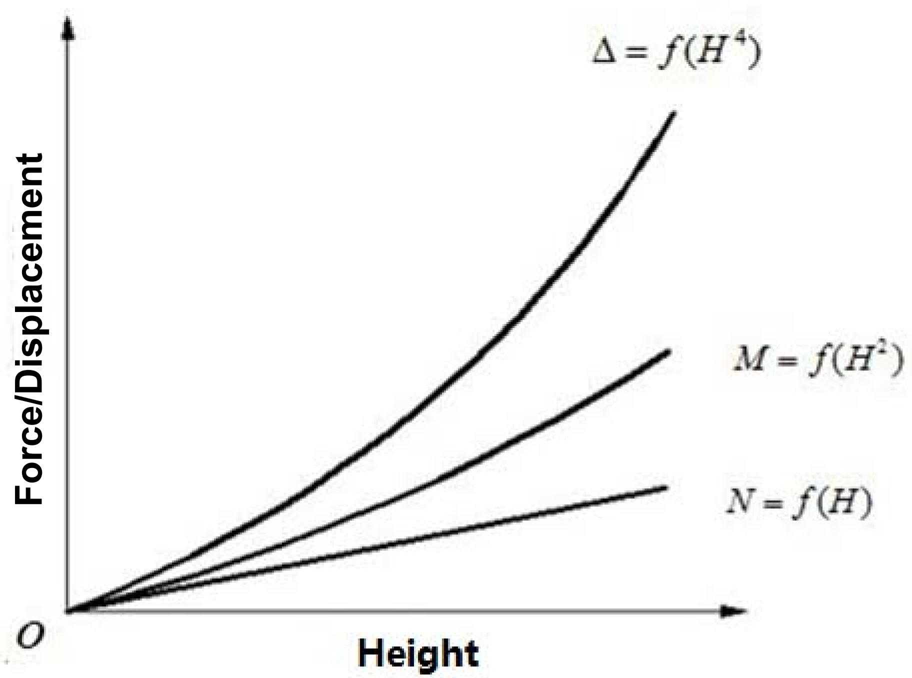
- The average height of the tallest buildings increases rapidly
- China holds the largest proportion of the world's top 100 tall buildings



Distribution of 100 Tallest Completed Buildings around the World

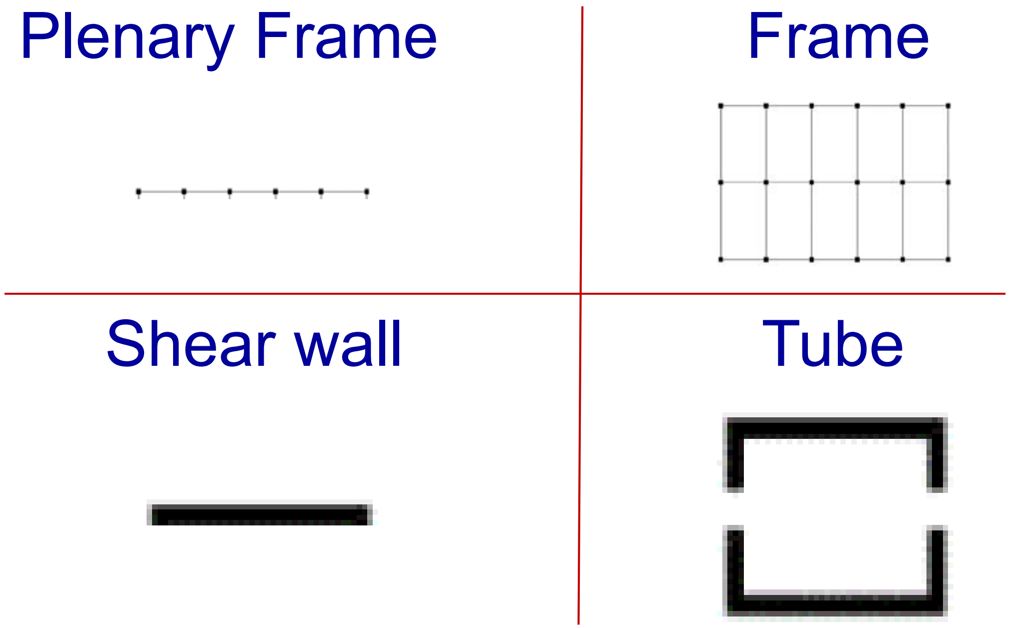
1. Background of Tall Buildings

1.2 Development of Tall Buildings



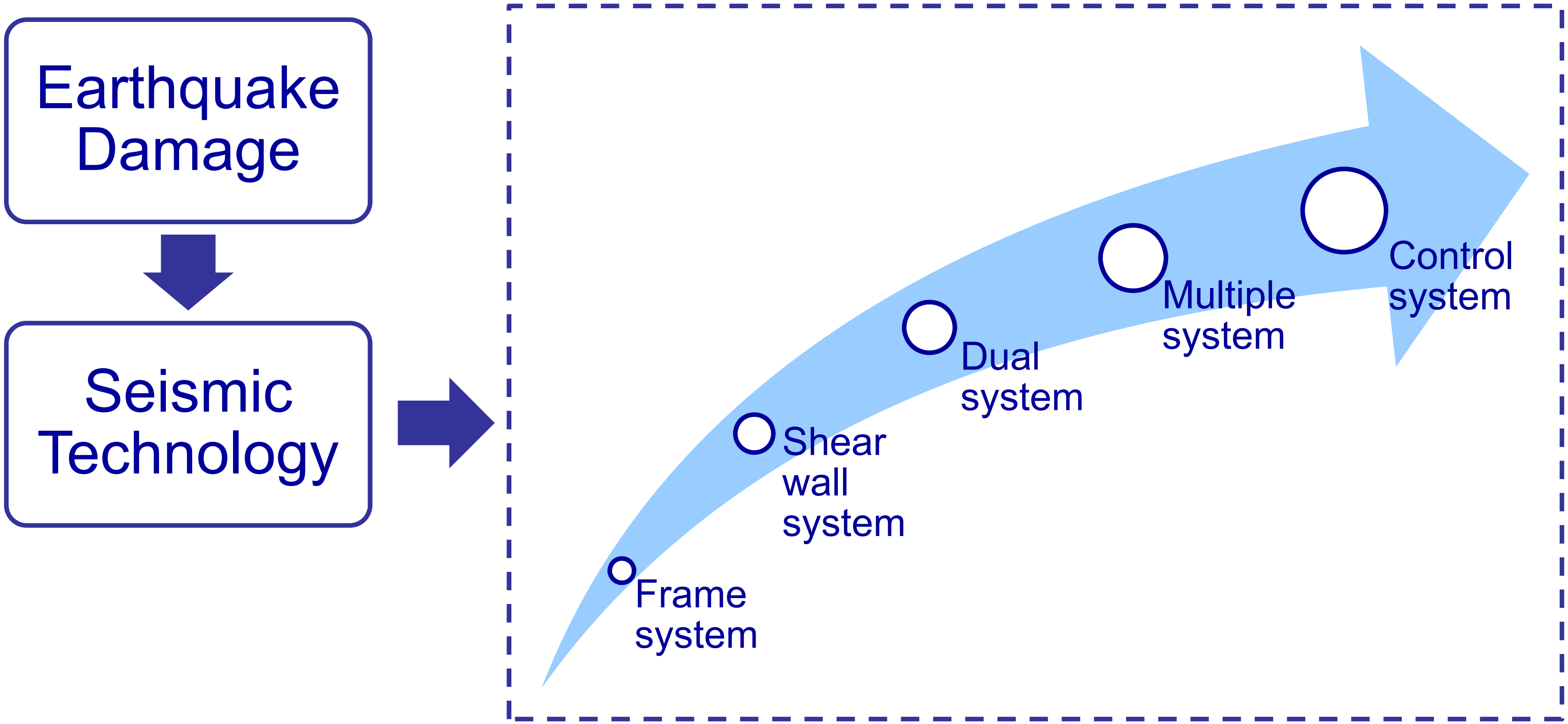
Force/displacement vs. Height

A balance of the height, material and system

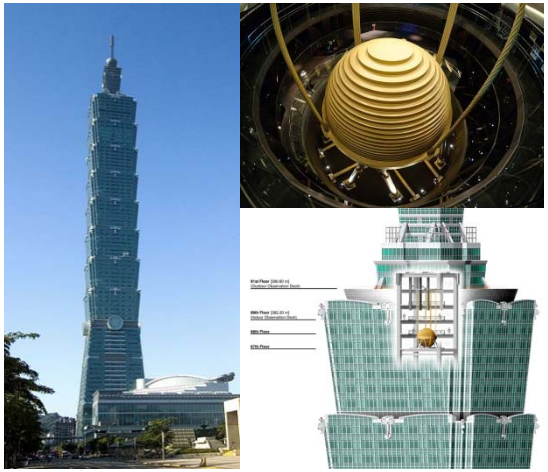
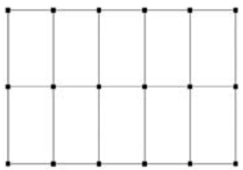
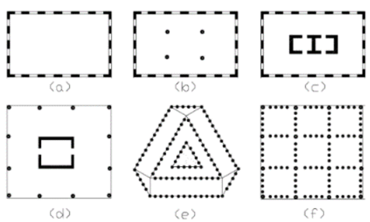
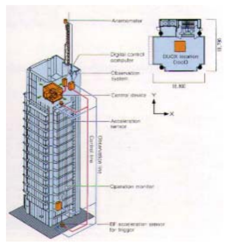
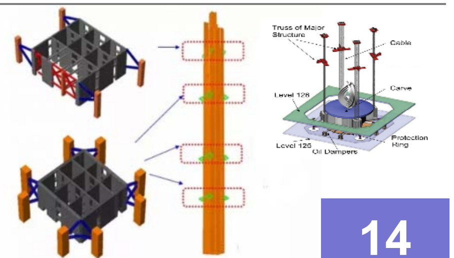


- **Frame**
- **Shear wall**
- **Frame-shear wall structure**
- **Frame-tube structure**
- **Tube-in-tube structure**
- **Bundled tube structure**
- ***etc*.**

2. Structural Systems for Tall Buildings



2. Structural Systems for Tall Buildings

Frame system	Shear wall system	Dual system	Multiple system + Control system	
				
1947	1976	1990	2004	2015
Bund No.14	Baiyun Hotel	Bank of China	Taipei 101 Tower	Shanghai Center
37m	122m	315m	509m	632m
Shanghai	Guangzhou	Hong Kong	Taipei	Shanghai
				

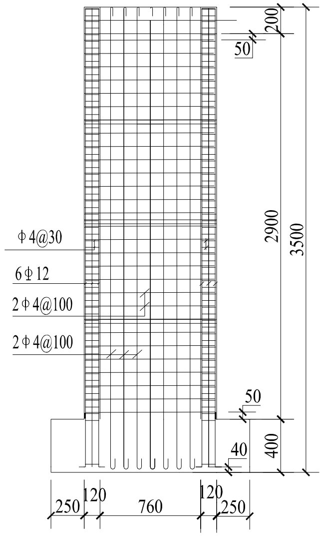
2. Structural Systems for Tall Buildings

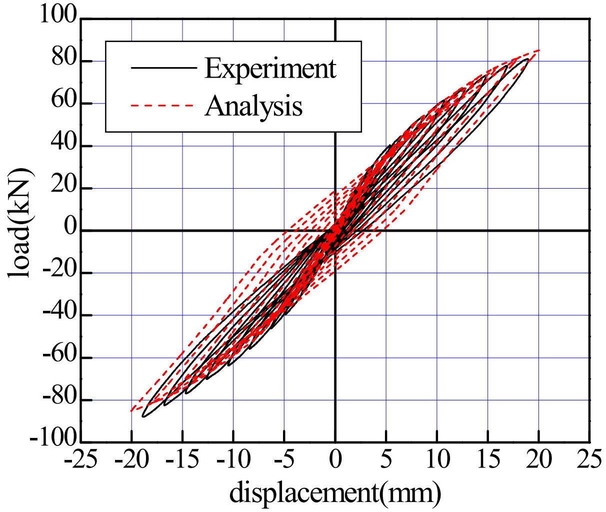
1	Structural Walls
2	Damped Outriggers
3	Eddy-current Tuned Mass Dampers
4	Ground Motion Selection
5	Dynamic Testing

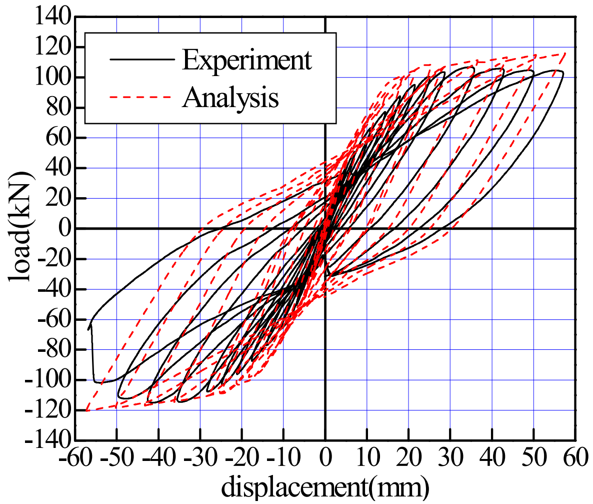
3. Structural Walls

3.1 Reinforce Concrete Shear Walls (1990s, Prof. X. Lu)

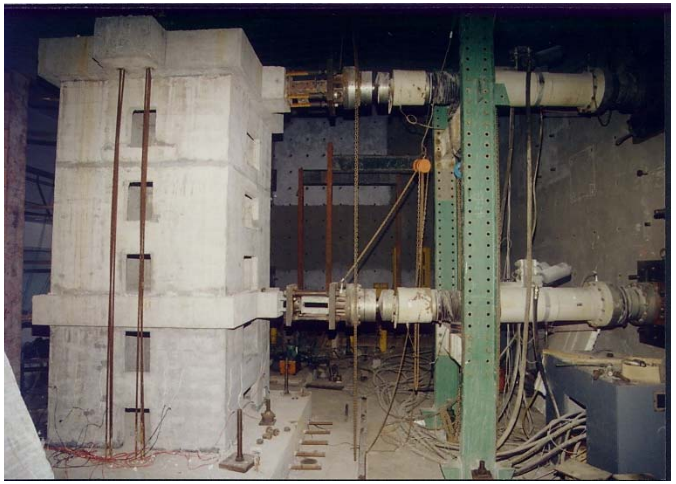
Shear Walls

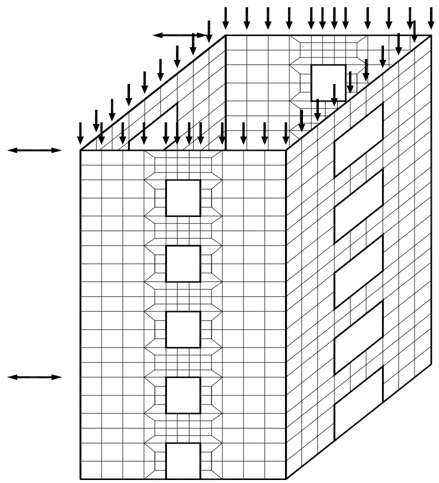






Tubes





3. Structural Walls

3.1 Reinforce Concrete Shear Walls (2000s, Prof. W. Cao)

Shear walls with diagonal reinforcement

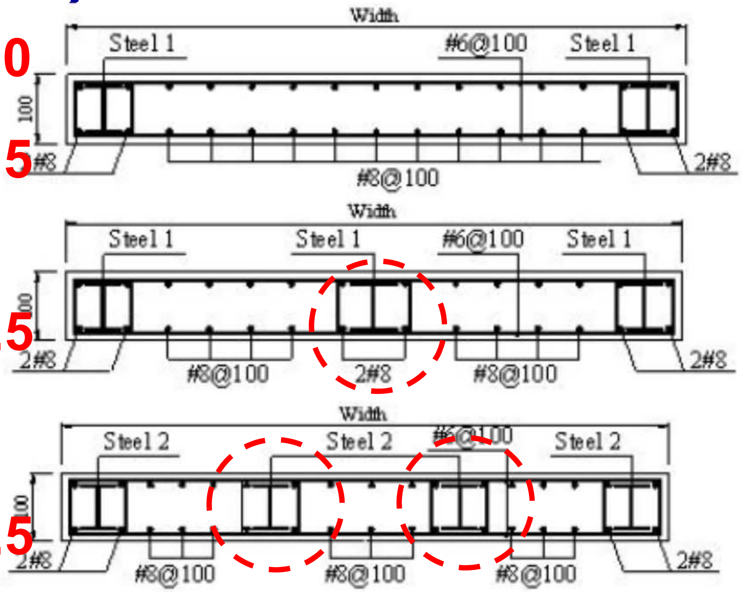
3.2 Composite Shear Walls (2000s)

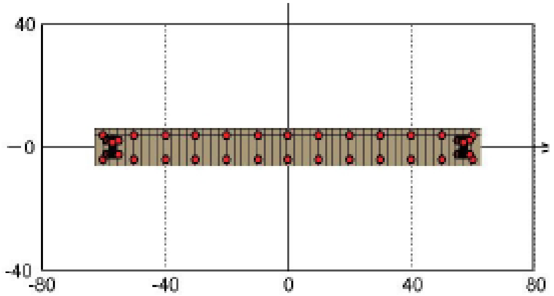
CSW-1: Height=2400 **2.0**
Width=1200

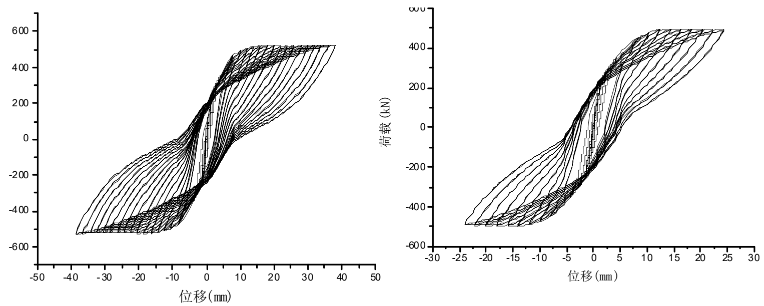
CSW-2: Height=1800 **1.5**
Width=1200

CSW-3: Height=1800 **1.5**
Width=1200

CSW-4: Height=1800 **1.5**
Width=1200





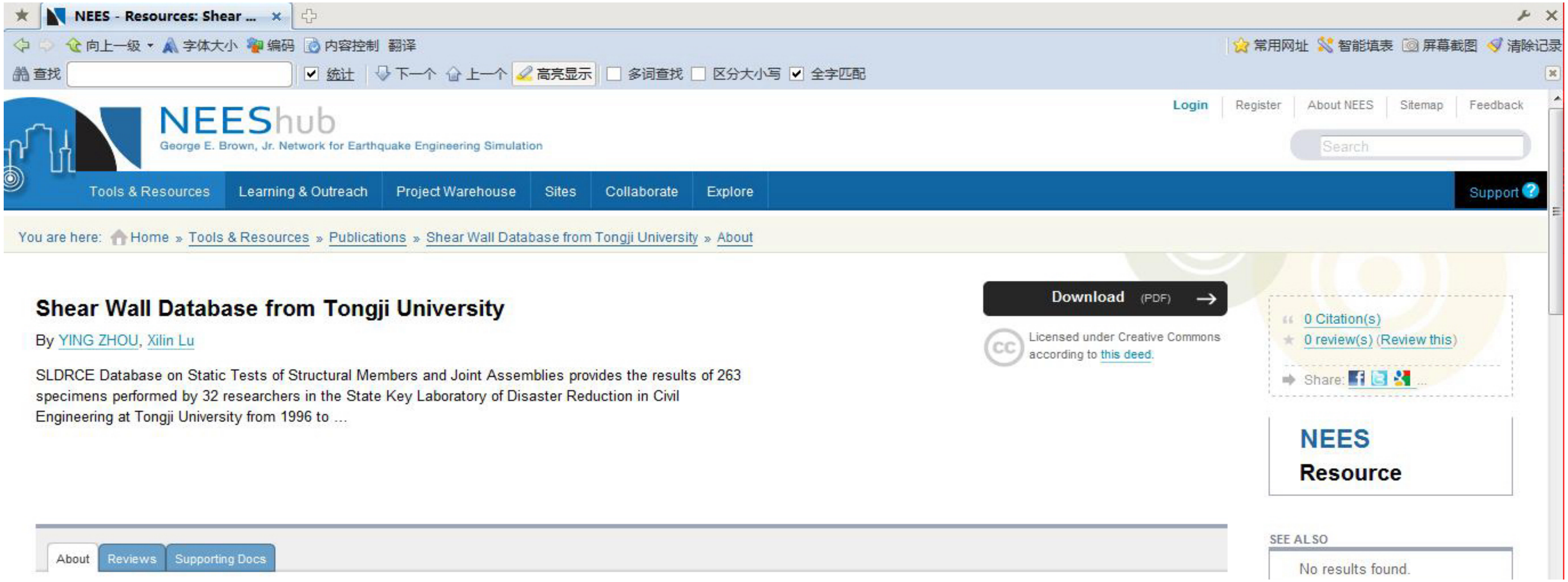


Shear walls with embedded steel

Ying Zhou, *et al*. Seismic behavior of composite shear walls with multi-embedded steel sections. STRUCT DES TALL SPEC. 19(6): 618-636, 2010.

3.3 Shear Wall Database from Tongji University (2010, Prof. Y. Zhou and X. Lu)

http://nees.org/resources/869 (83 shear walls)

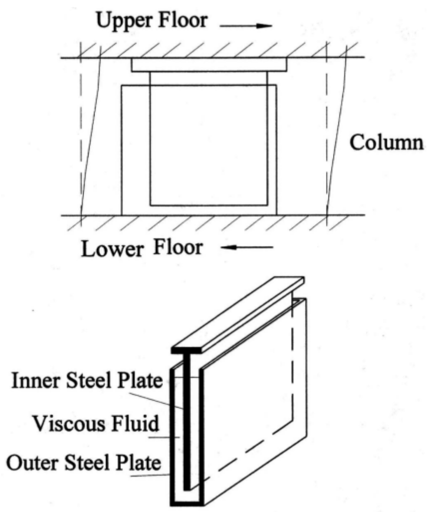


3. Structural Walls

After 2008 Wenchuan earthquake (M=8)

3. Structural Walls

3.4 Viscous Wall Dampers (2008, Prof. X. Lu and Y. Lu)



Performance test

Mechanical model

$$F_d = 18.5 f^{-0.15} e^{-0.043(T-28.3)} sign(\dot{x}) |\dot{x}|^{0.5}$$

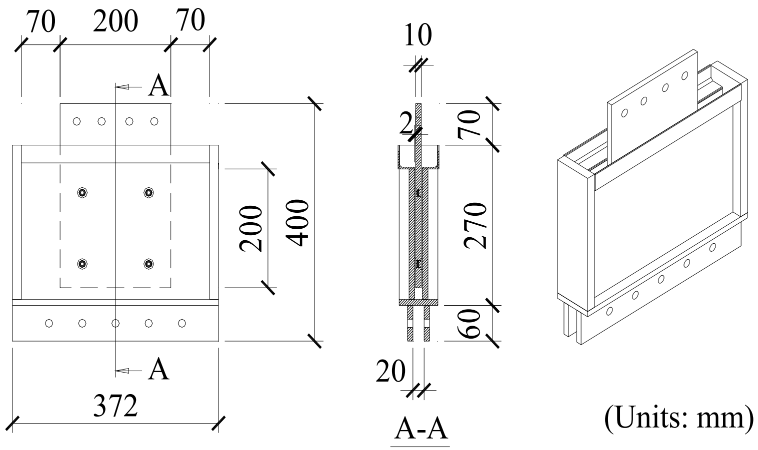
$$F_e = 400 f^{0.5}\, e^{-0.043(T-28.3)} x$$

Shaking table test

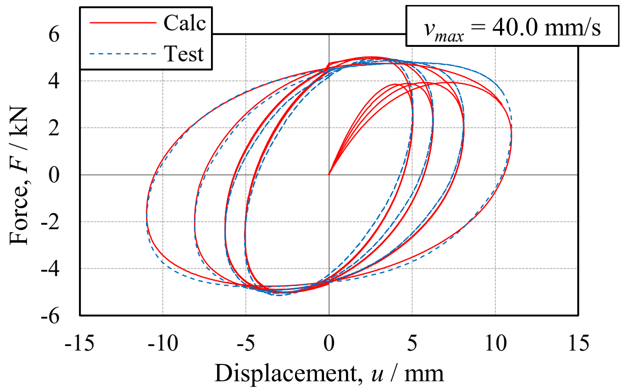
Xilin Lu, Ying Zhou, Feng Yan. Shaking table test and numerical analysis of RC frames with viscous wall dampers. J STRUCT ENG-ASCE. 134(1): 64-76. 2008

3. Structural Walls

3.4 Viscous Wall Dampers (2010s, Prof. Y. Zhou)



I. Performance Test



II. Generalized Maxwell model:

$$\dot{F}(t) = \left(\dot{u}(t) - \mathrm{sign}(F(t)) \times \left|\frac{F(t)}{C}\right|^{1/\alpha}\right) \times K$$

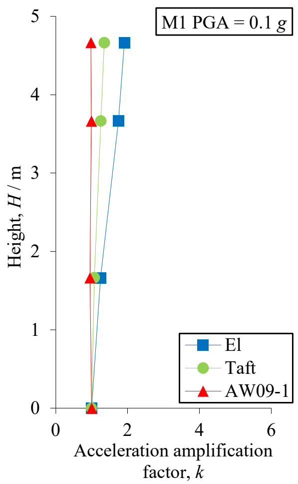
$$K = 4.457 \times \left(u^2(t) + v^2(t) \times \left|\frac{u(t)}{a(t)}\right|\right)^{-0.3014} + 0.1968$$

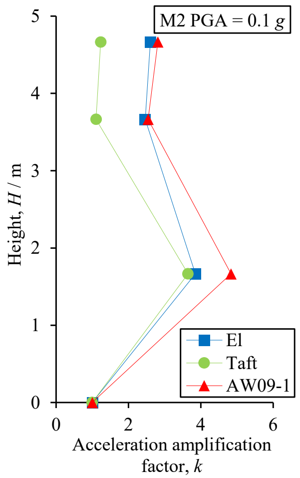
$$C = 0.7845 \times (|a(t) \times u(t)| + v^2(t))^{-0.1948} \times \left(0.0590 \times \sqrt{\left|\frac{a(t)}{u(t)}\right|} + 1.0\right)$$

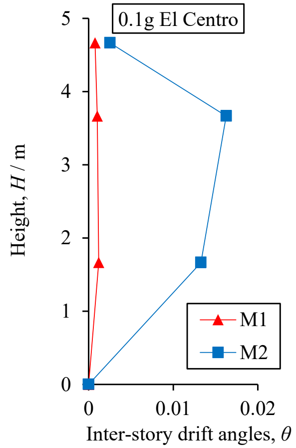
3. Structural Walls

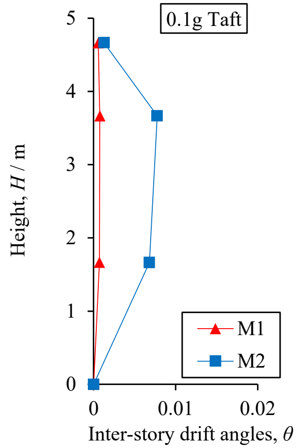
3.4 Viscous Wall Dampers (2010s, Prof. Y. Zhou)

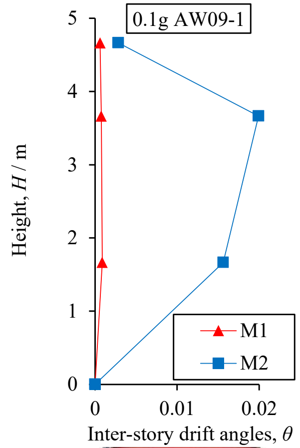
III. Shaking table test & dynamic elasto-plastic analysis



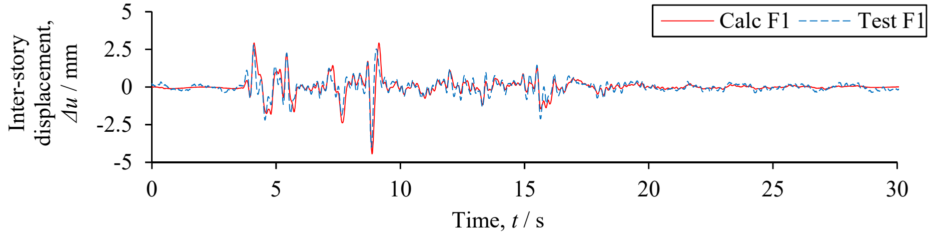




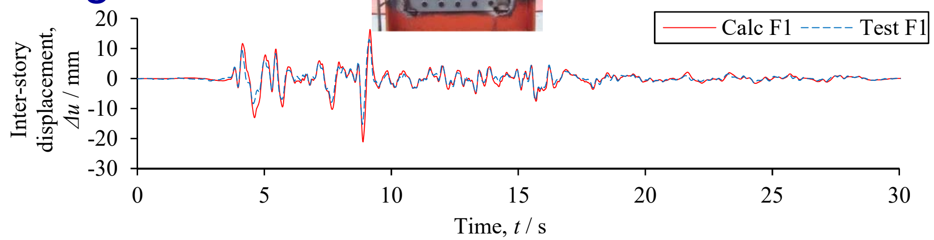




0.2g El Centro



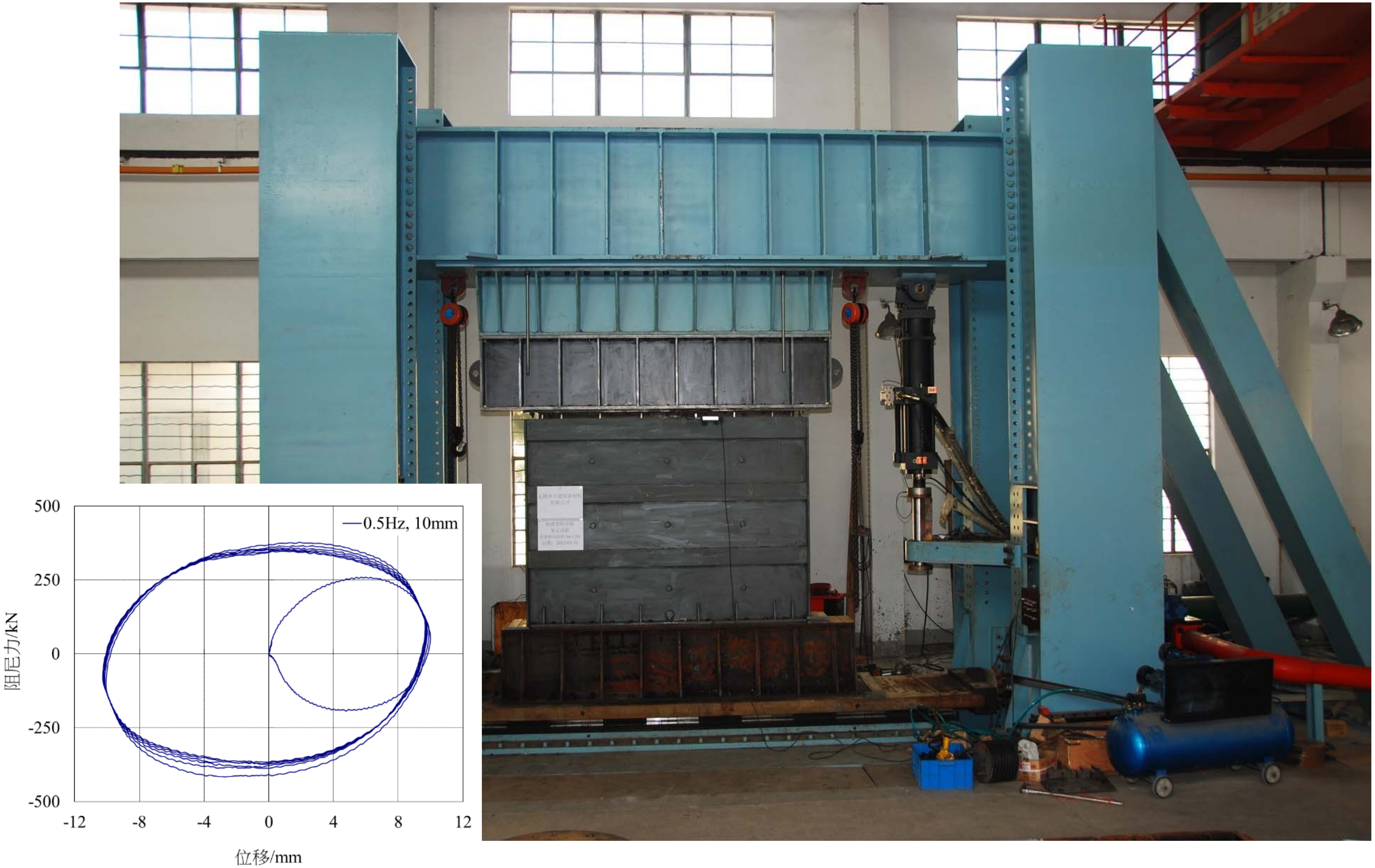
0.7g El Centro



Ying Zhou, Peng Chen, Dan Zhang, *et al*. Study on shaking table test of a steel frame with viscous wall dampers. (under review, ENG STRUCT)

3. Structural Walls

Full scale test (VWD－NL×850×60, FUYO, China)

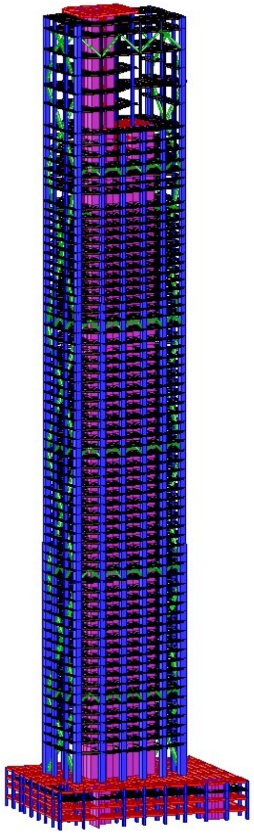


3. Structural Walls

3.4 Viscous Wall Dampers (2010s, Prof. Y. Zhou)

IV. Application of VWDs

Tangshan Residential Building
(32-story, 66 x 40T)

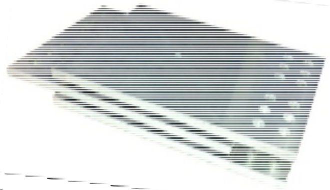


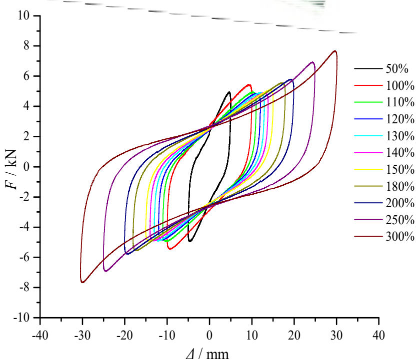
Xianmen International Center
(340m, 90 x 170ton)

Shimao International Plaza
(Retrofitting)

3.5 Viscoelastic Dampers with Strong Nonlinearity (2010s, Prof. Y. Zhou)

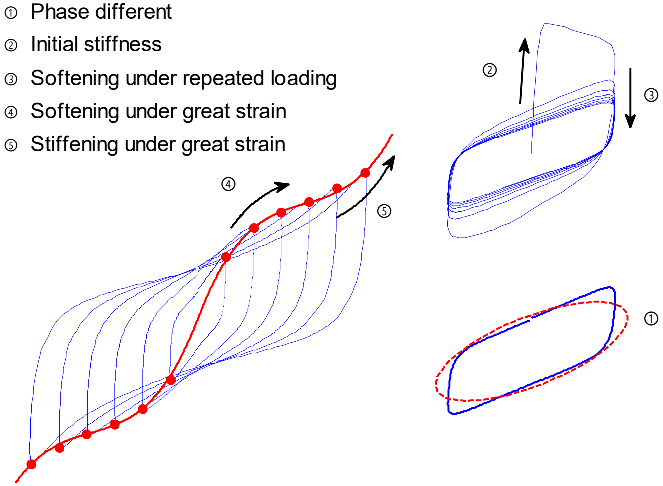
I. Performance tests





Nonlinearity resources

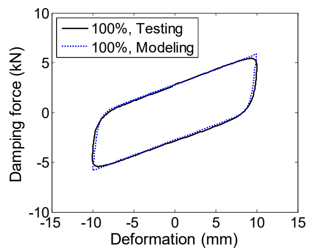
① Phase different
② Initial stiffness
③ Softening under repeated loading
④ Softening under great strain
⑤ Stiffening under great strain

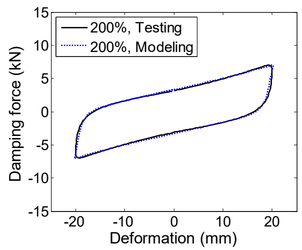


II. Mechanical model

$$\begin{cases} F = \lambda_1 \lambda_2 \left(F_1 + F_2\right) \\ F_1 = k(u + \alpha z) \\ F_2 = a u^3 + b u \\ \dot{z} = \dot{u} - \beta(|\dot{u}||z|^{n-1} z - \dot{u}|z|^n) \end{cases}$$

$$\begin{cases} k = 0.0937 + 0.193 e^{0.97 - 0.1 u_0} \\ \beta = 0.436 + 1.47 e^{0.83 - 0.17 u_0} \end{cases}$$



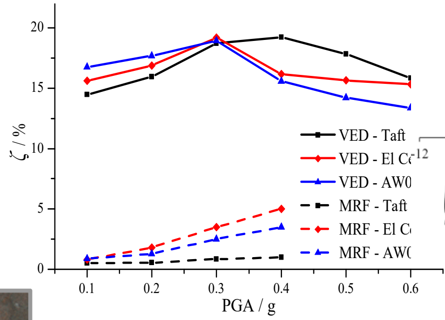


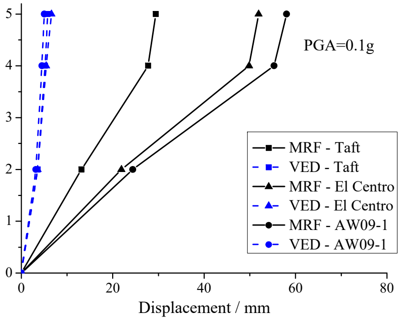
3. Structural Walls

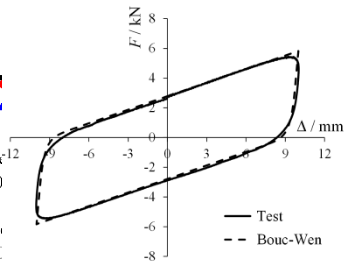
3.5 Viscoelastic Dampers with Strong Nonlinearity (2010s, Prof. Y. Zhou)

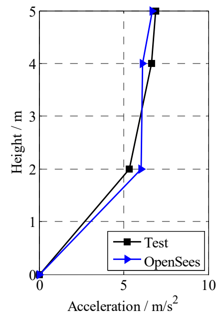
III. Shaking table test

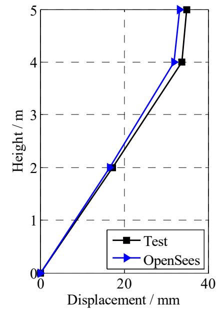
Numerical simulation

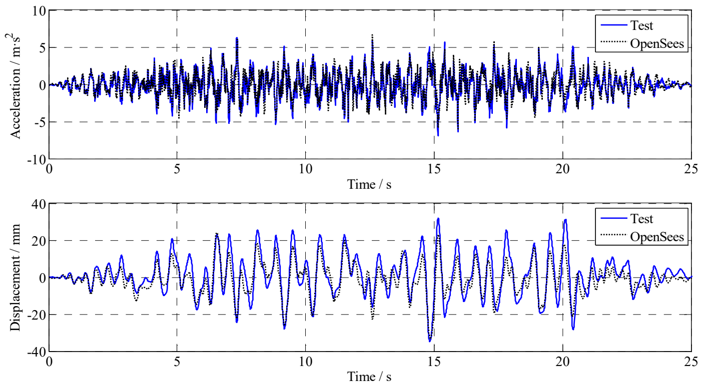












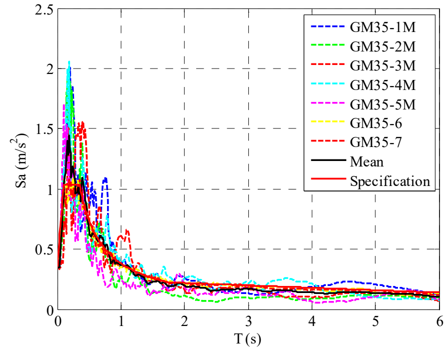
S. Gong, Y. Zhou. Experimental study and numerical simulation on a new type of viscoelastic damper with strong nonlinear characteristics. STRUCT CONTROL HLTH, 2017; 24: e1897.

3. Structural Walls

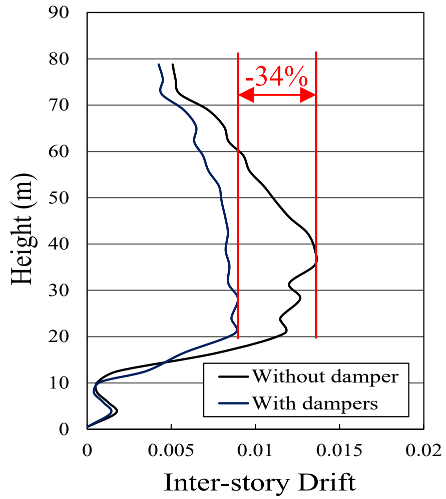
3.5 Viscoelastic Dampers with Strong Nonlinearity (2010s, Prof. Y. Zhou)

IV. Application in Dabao'en Temple
(Steel structure, 99m, 112 VEDs)

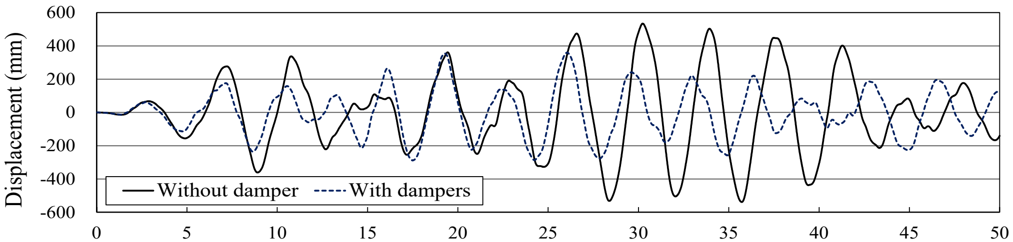
Performance test of VED



S_a of ground motions



Control effect

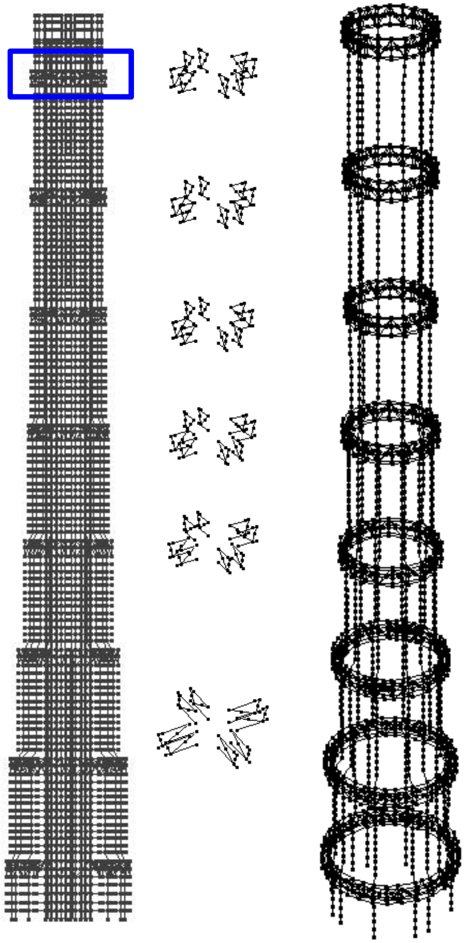


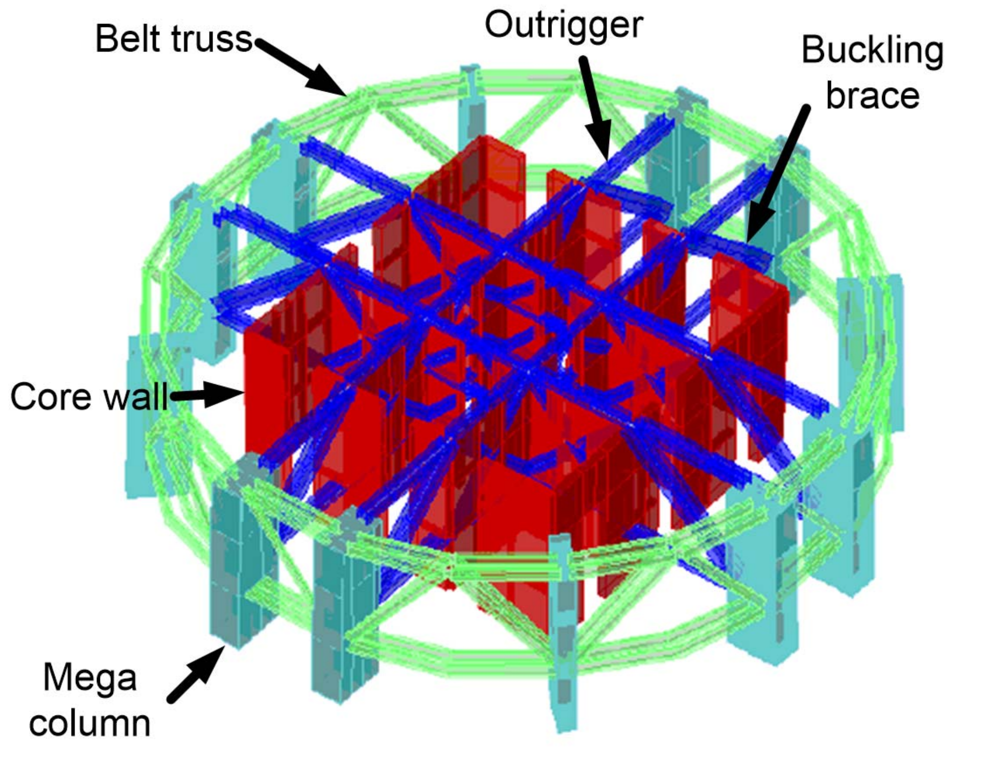
Comparison of top displacement

S. Gong, Y. Zhou, P. Ge. Seismic analysis of for tall and irregular temple buildings: A case study of strong nonlinear viscoelastic dampers. STRUCT DES TALL SPEC. 2017, tal.1352

4. Damped Outriggers

4.1 Introduction





(a) Conventional outrigger

Shanghai Center Tower

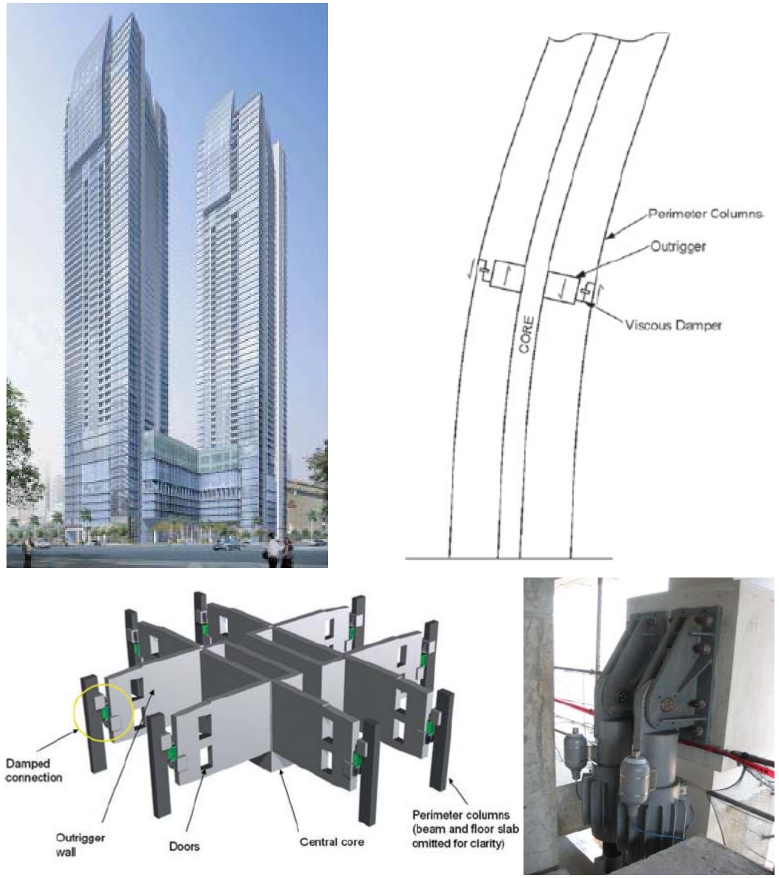
4.1 Introduction

With outriggers:

- **Good**
  - The stiffness is helpful to the control of inter-story drift under wind and earthquakes.
  - The overturning moment is balanced between peripheral frame and central core walls.
- **Bad**
  - The change of stiffness would form the vulnerable stories under strong earthquakes.

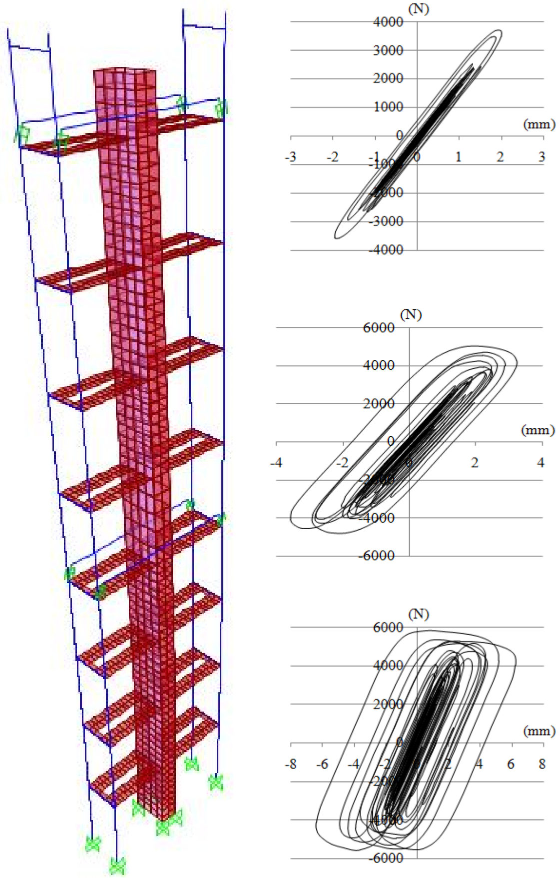
4. Damped Outriggers

4.1 Introduction



Manila, Philippine (ARUP)

Test in Guangzhou

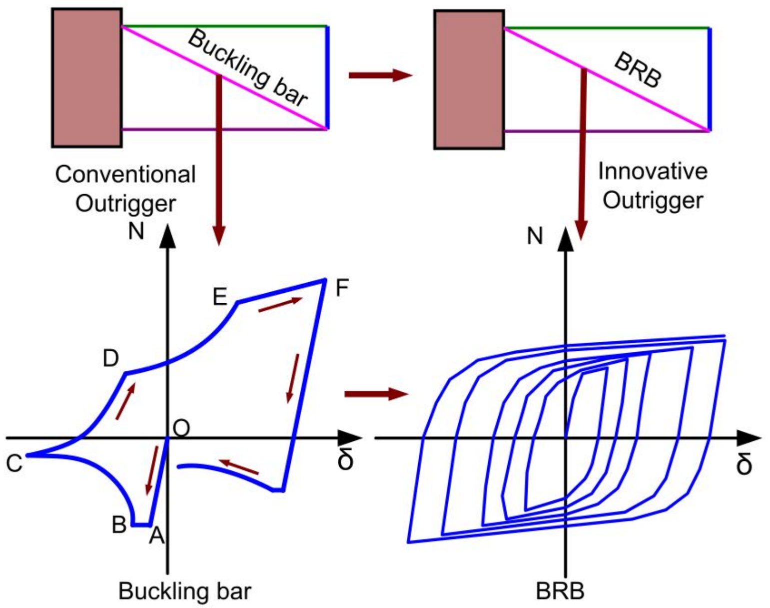


Numerical analysis

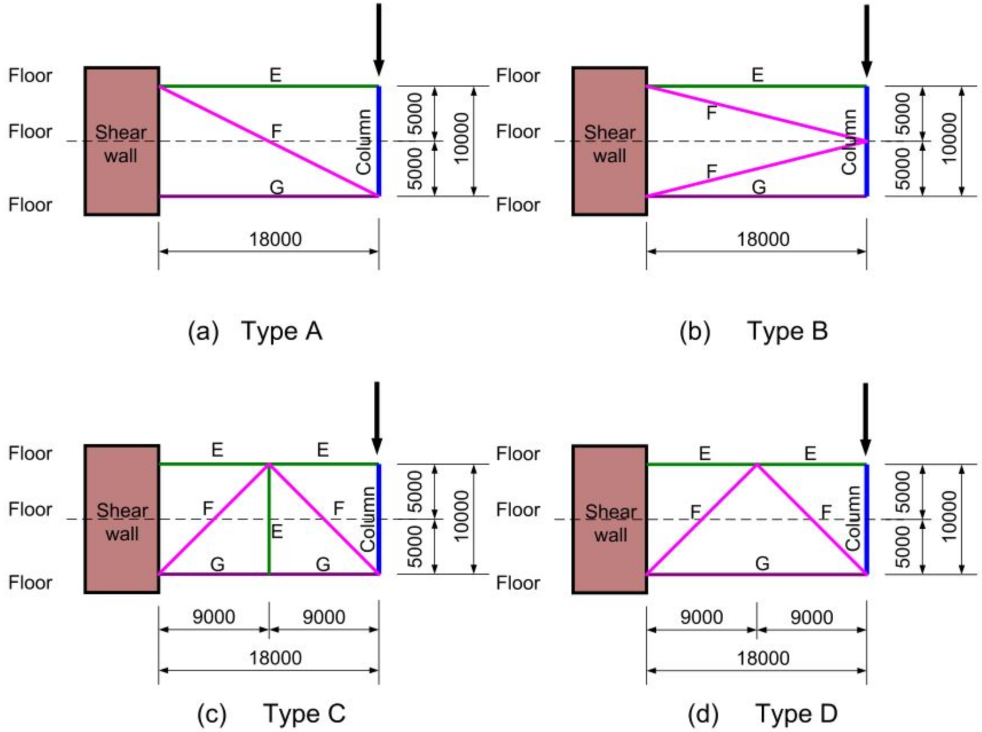
Ying Zhou, Hexian Li. Analysis of a high-rise steel structure with viscous damped outriggers. STRUCT DES TALL SPEC, 23(13): 963–979, 2014.

4. Damped Outriggers

4.2 Damped Outrigger with BRB



Comparison of hysteretic loops

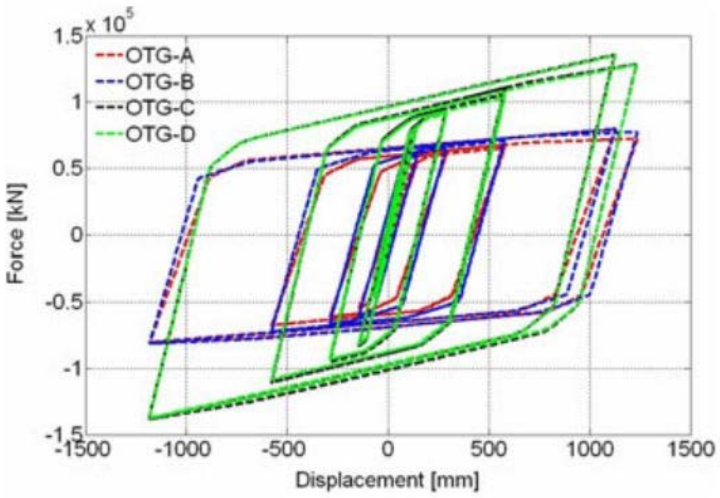


Four configurations

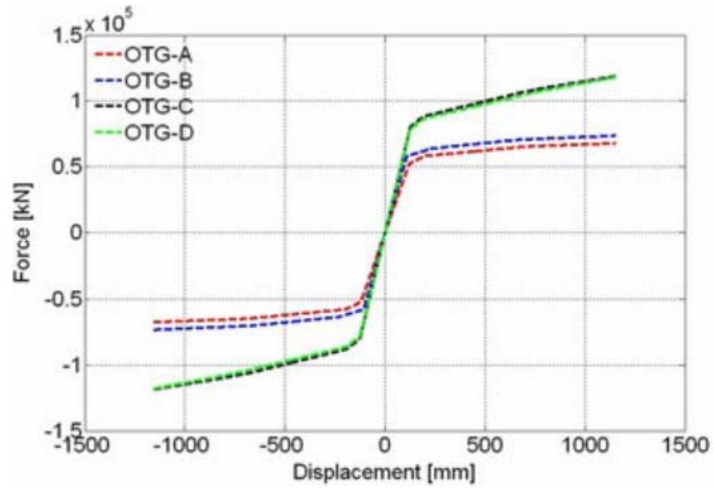
Ying Zhou, Cuiqiang Zhang, Xilin Lu. Seismic performance of a damping outrigger system for tall buildings. STRUCT CONTROL HLTH, 2017, stc.1864.

4. Damped Outriggers

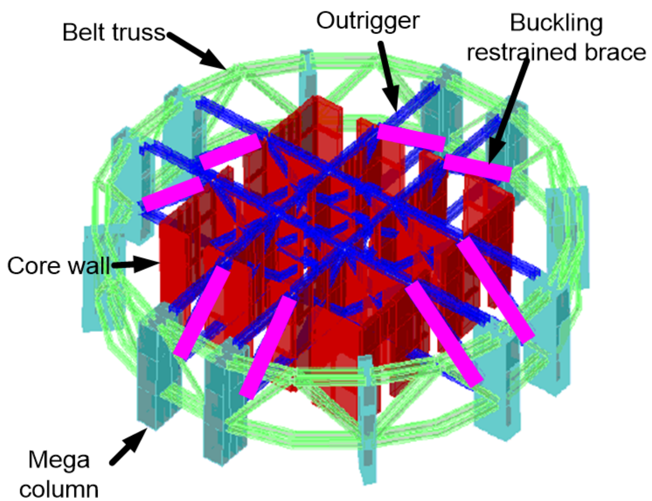
4.2 Damped Outrigger with BRB



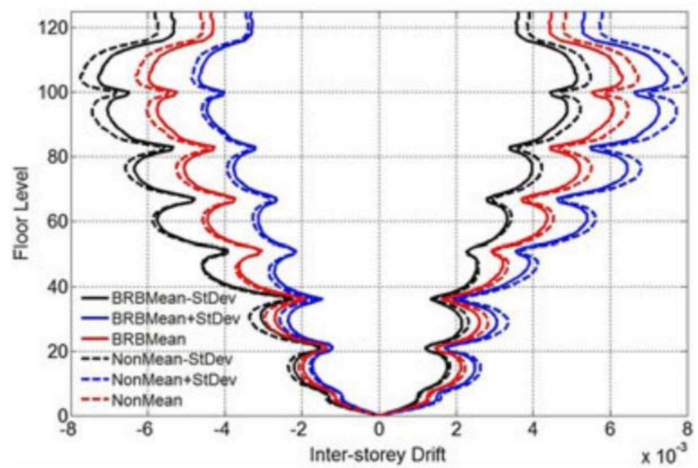
Hysteretic loops



Back bone curves



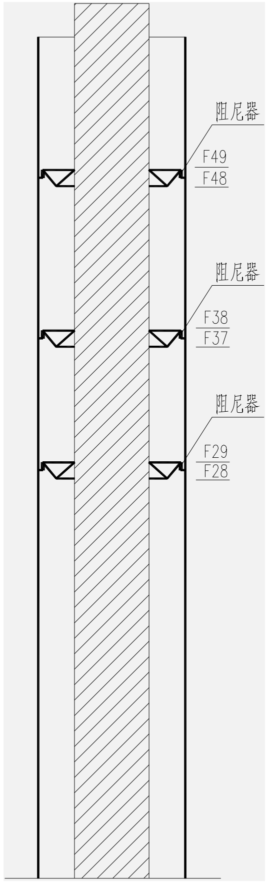
(b) Damping outrigger

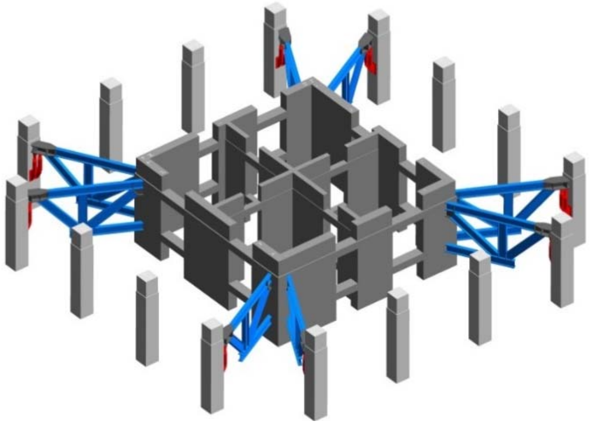


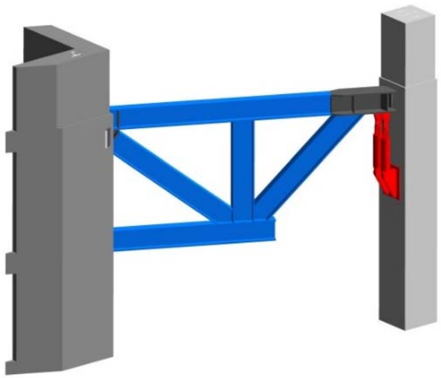
Comparison of IDRs

4. Damped Outriggers

4.3 Damped Outrigger Project in China
(East China Architectural Design and Research Institute)



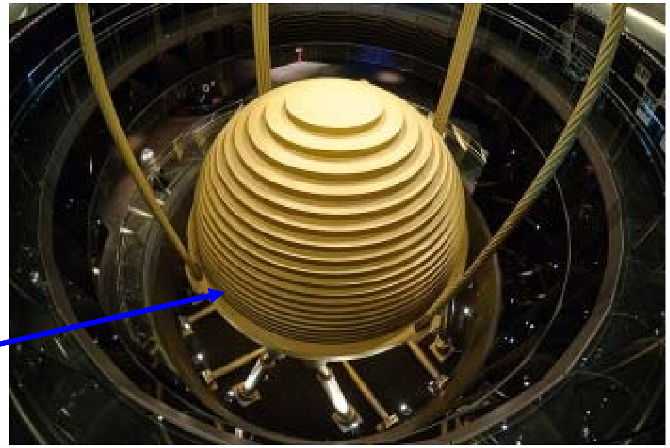




Urumqi Greenland Center (258m)

5. Eddy-current Tuned Mass Dampers

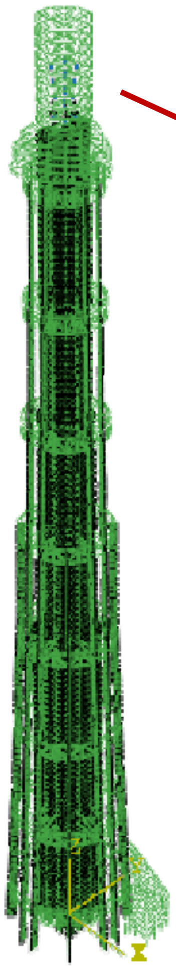
5.1 Tuned Mass Damper

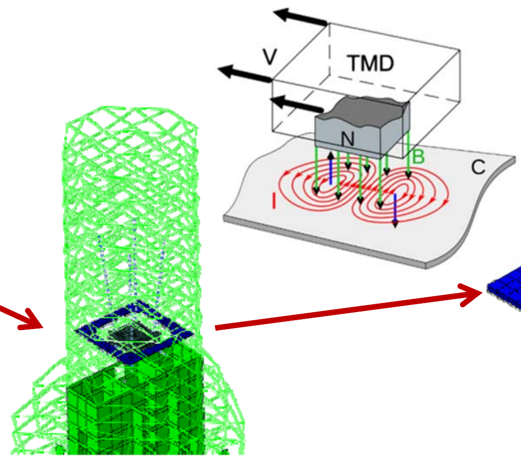


509-meter-tall Taipei 101

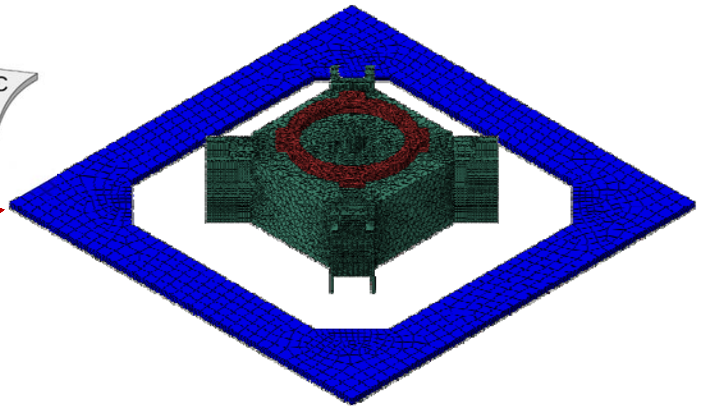
5. Eddy-current Tuned Mass Dampers

5.2 Shanghai Center Tower (Prof. X. Lu and Z. Zhou)

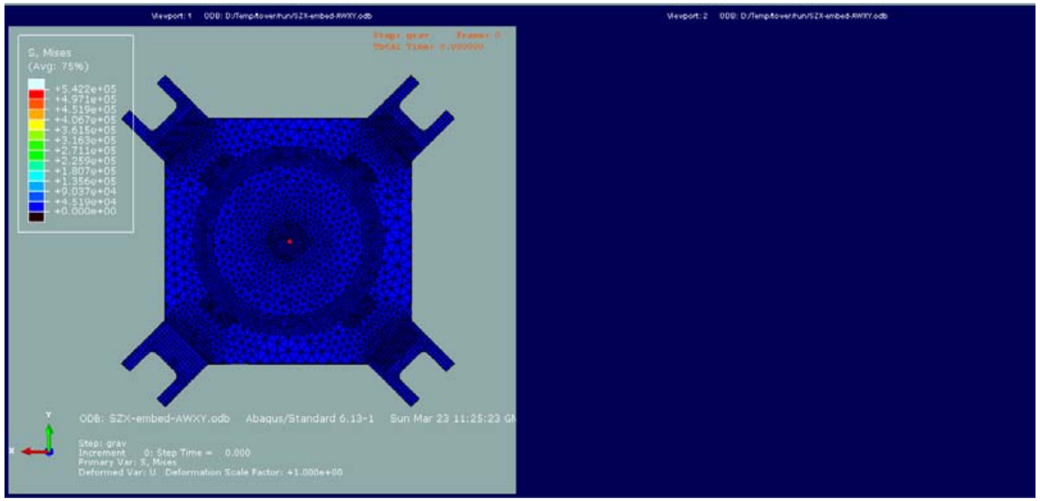




Eddy-current TMD



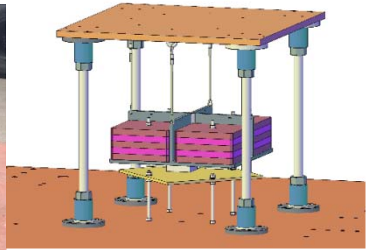
Building with ETMD under one earthquake input

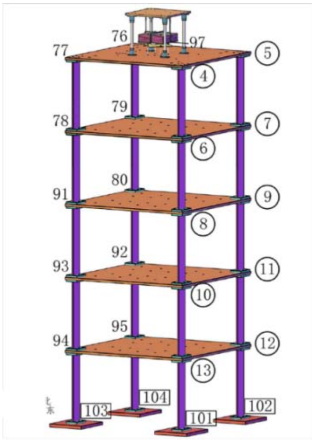


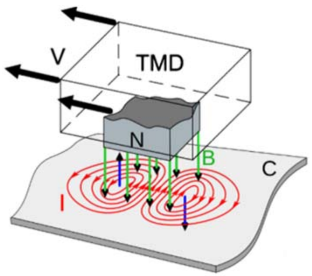
5. Eddy-current Tuned Mass Dampers

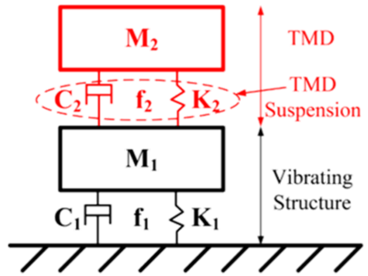
5.3 ETMD (Applied in Shanghai Center Tower)

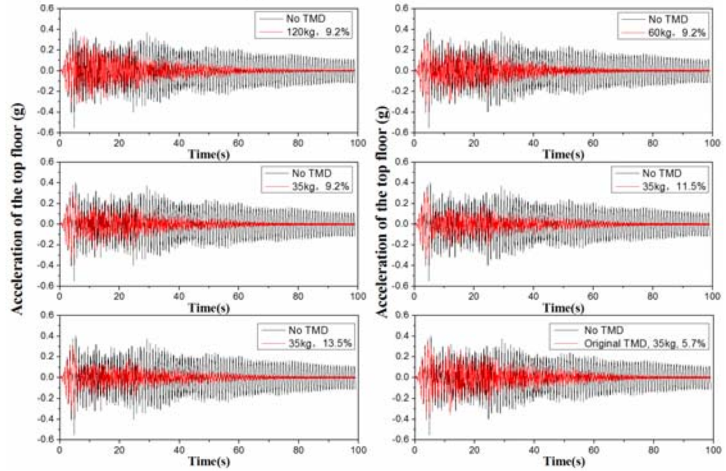
Eddy-current TMD can effectively attenuate the response of undamped primary system with a small weight penalty (1%-2%). The RMS values of acceleration response of the top floor were reduced up to 60%.







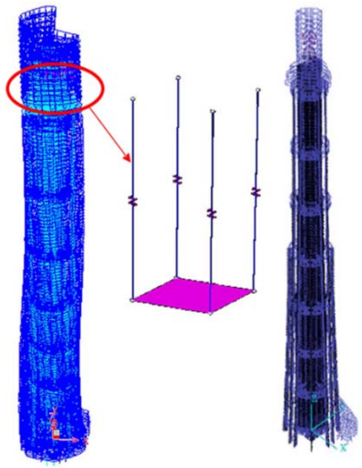


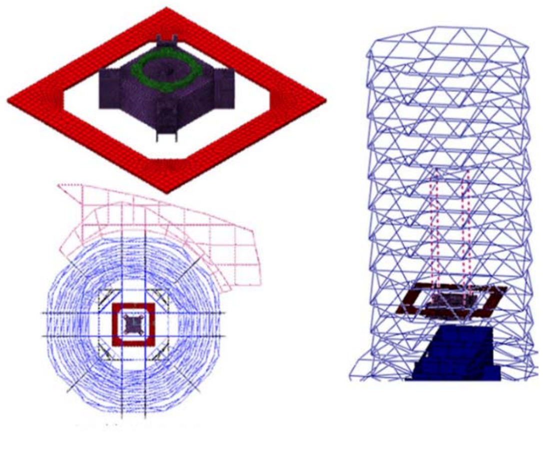


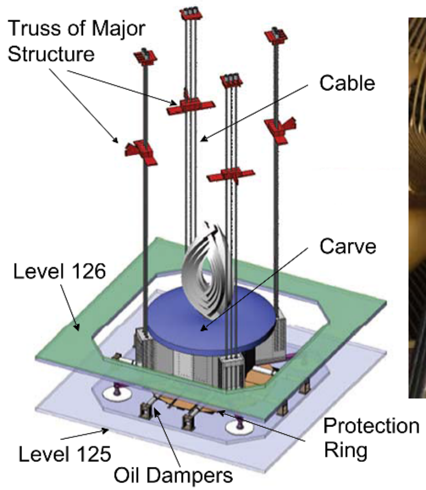
5. Eddy-current Tuned Mass Dampers

5.3 ETMD (Applied in Shanghai Center Tower)

A 1000 ton eddy-current TMD was set up on the 125th floor of Shanghai Center Tower, a 632m super-tall building. The TMD can attenuate the acceleration response of top floor by 45%-60% under wind load with long periods, and has relatively insignificant beneficial effects but no adverse effects under earthquakes.


Sap2000 Model


Abaqus Model



Xilin Lu, Qi Zhang*, Dagen Weng, *et al*. Improving performance of a super tall building using a new eddy-current tuned mass damper. STRUCT CONTROL HLTH, 2016, stc.1882

6. Peer Review of Tall Buildings

Conceptual design → Preliminary design

↓

Review panel

(1) Ground Motion Selecti-on	(2) Nonlinear analysis of the structure	(3) Dynamic test of the structure	(4) Static test of weak joints	(5) Site measurement of dynamic property

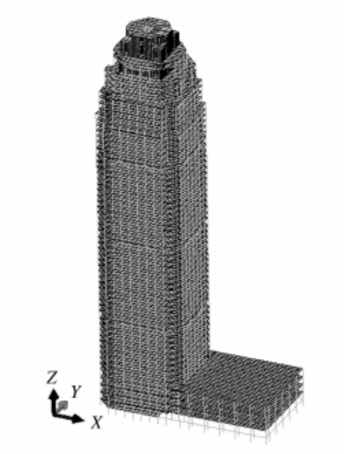
↓

Construction drawings

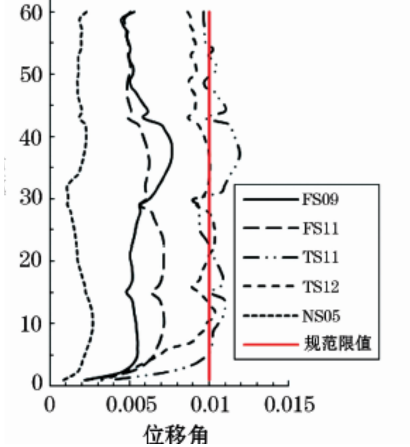
6. Peer Review of Tall Buildings

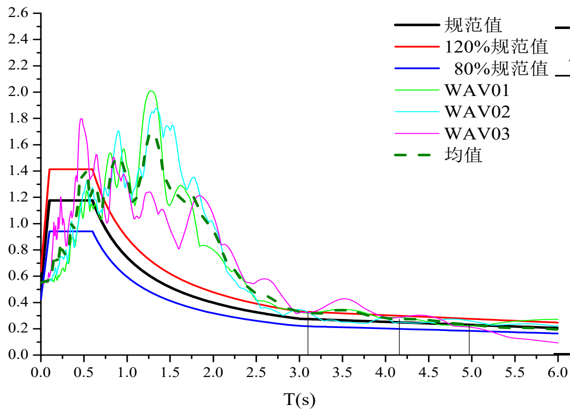
6.1 Ground Motion Selection

Problems



Limitation

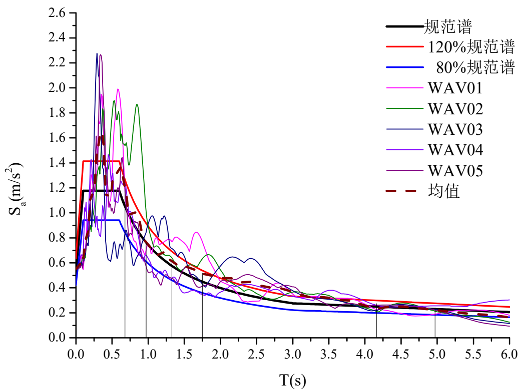




输入	X 向	比值	Y 向	比值
反应谱分析	41.16	100%	37.00	100%
WAV01	98.39	239%	56.10	152%
WAV02	83.13	202%	52.26	141%
WAV03	62.82	153%	46.82	127%
均值	81.45	198%	51.73	140%
最小值	62.82	153%	46.82	127%
最大值	98.39	239%	56.10	152%

NO

Solutions



输入	X 向	比值	Y 向	比值
反应谱分析	41.16	100%	37.00	0%
WAV01	42.65	104%	36.31	98%
WAV02	38.70	94%	28.15	76%
WAV03	43.33	105%	36.63	99%
WAV04	35.90	87%	40.85	110%
WAV05	38.32	93%	34.27	93%
均值	39.78	97%	35.24	95%
最小值	35.90	87%	28.15	76%
最大值	43.33	105%	40.85	110%

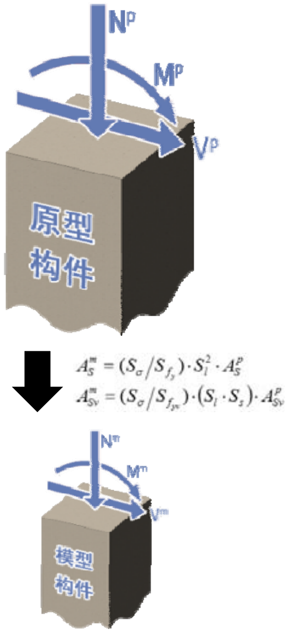
YES

Applications (19)

6. Peer Review of Tall Buildings

6.2 Shaking Table Testing Technology

Problems



- Classic similitude theory?
- Composite material?
- Sound interpretation?
- Nonlinear damper?

Solutions

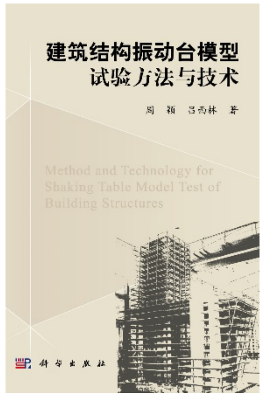
I. Quasi-static method

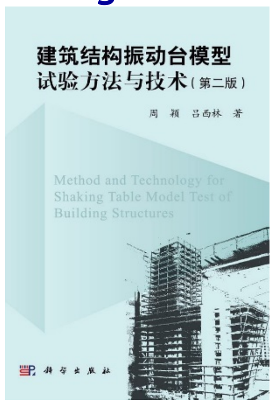
II. Equivalent internal force method

$$m\left(\ddot{x}(t)+\ddot{x}_g(t)\right)+c\dot{x}(t)+kx(t)=0 \rightarrow \frac{S_E}{S_\rho S_a S_l}=1 \rightarrow S_c = S_\sigma \cdot \sqrt{\frac{S_l^3}{S_a}}$$

物理量 质量 系统量纲	已知物理量			未知物理量量纲的线性列变换		
	L	σ	a	c	$2c-2\sigma+a$	$2c-2\sigma+a-3L$
[M]	0	1	0	1	0	0
[L]	1	−1	1	0	3	0
[T]	0	−2	−2	−1	0	0

Method and Technology for Shaking Table Model Test of Building Structures





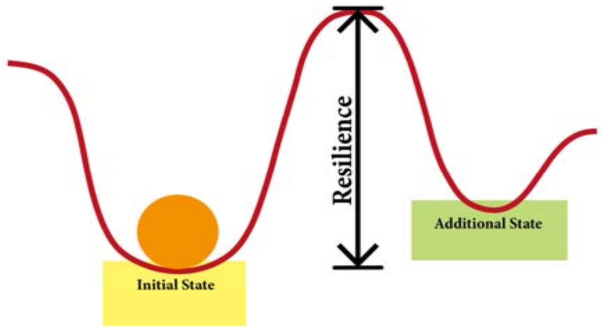
I have a dream…

Intelligent high-rise building and structure

7.1 Definition

◻ Resilience

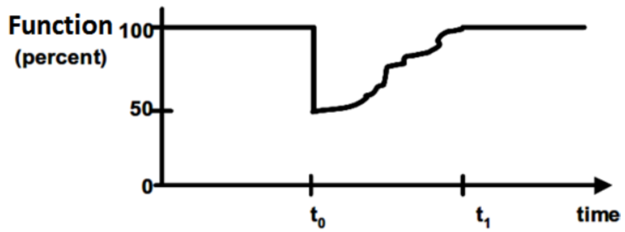
A resilient system returns to an equilibrium state after disturbance. Most resilient systems have multiple equilibrium points.



Resilient system

◻ Earthquake resilient structures

A resilient structure refers to structures that do not need to repair or only need slightly repair to restore their function after earthquake.



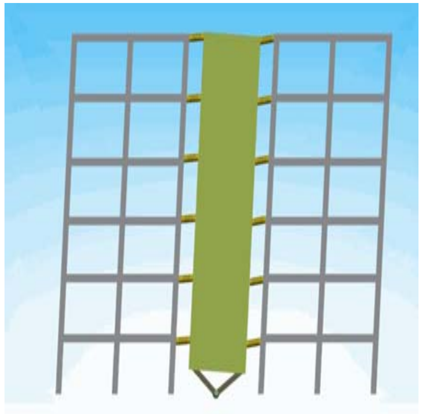
Earthquake resilience concept

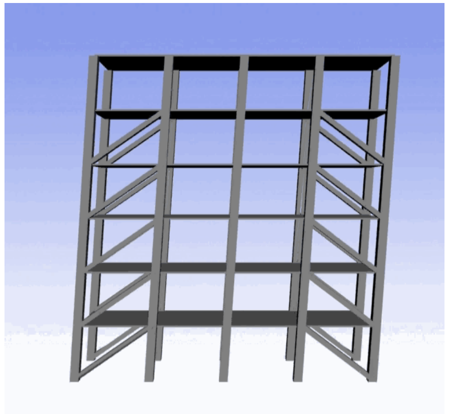
7. Earthquake Resilience

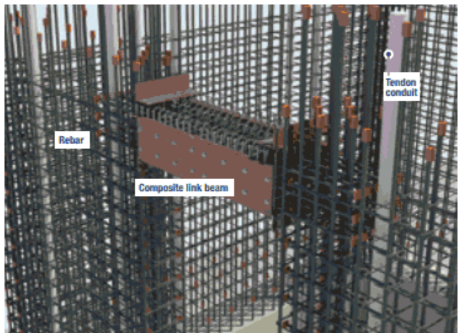
7.2 Technology

Technologies for resilient structures

- Rocking structures
- Self-centering structures
- Replaceable components
- Replaceable energy dissipation devices





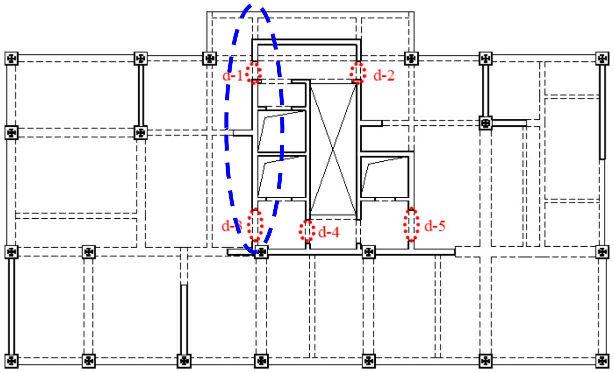


Ying Zhou, Xilin Lu. State-of-the art on rocking and self-centering structures. Journal of Building Structures in China. 32(9): 1-10, 2011.

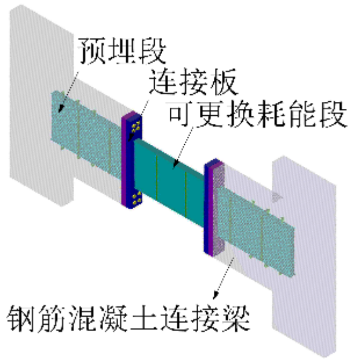
7. Earthquake Resilience

7.3 Engineering Application—China

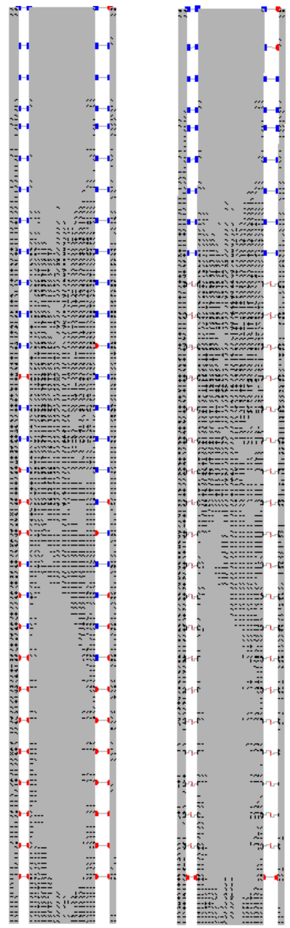
New construction: 29-story residential housing building in Xi'an, 2014



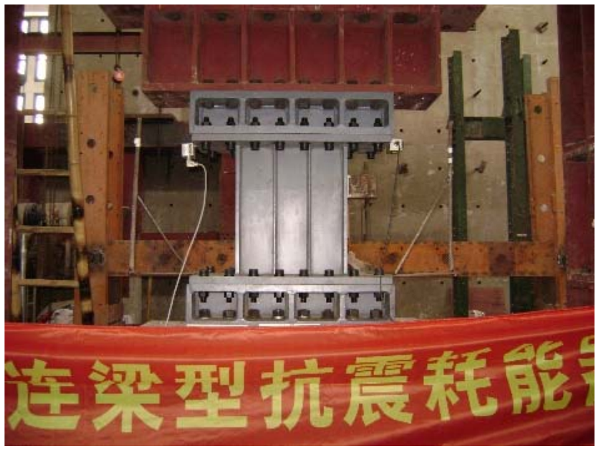
Plan layout of replaceable coupling beam



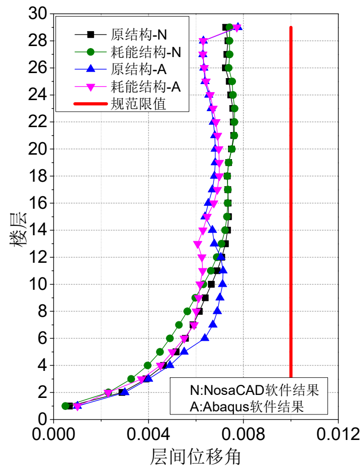
Connection for replaceable coupling beam



Damage contrast



Performance test



Seismic response

8. Future Direction

8.1 High Performance Structure

New Material

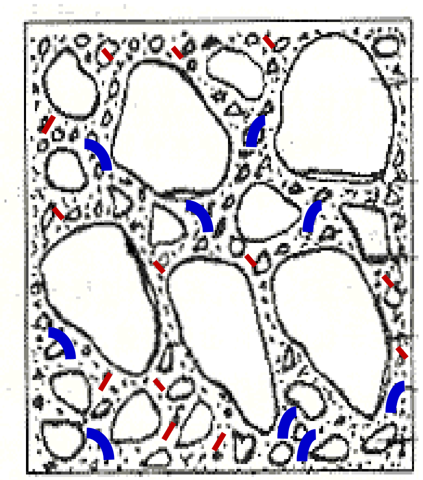
High performance material

New Component

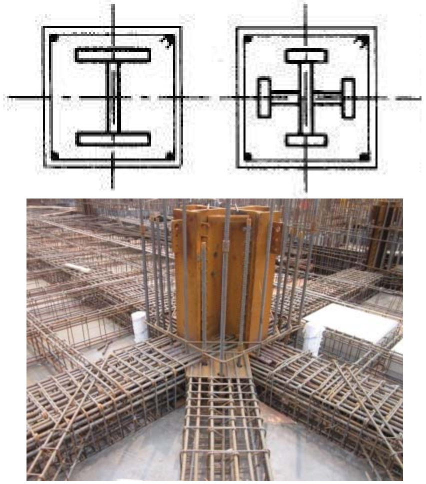
High performance component

New System

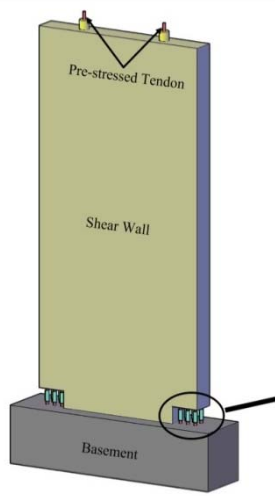
High performance system



High performance concrete



Steel reinforced concrete column



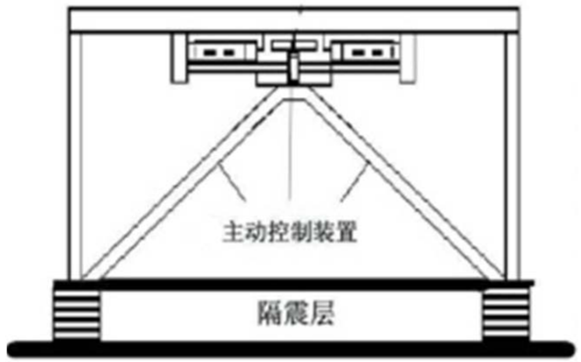
Self-centering shear wall with replaceable feet

8. Future Direction

8.2 Combined Technology (Cross-disciplinary)

Drone

TMD + damper



Isolation +
active control

COMBINED TECHNOLOGIES, BETTER PERFORMANCE!

Thanks!

E-mail: yingzhou@tongji.edu.cn