Frontier Report on Structural Engineering Research --- Tongji Graduates Lecture

Tall Building Seismic Research:
Structural analysis and testing, Structural passive control with application

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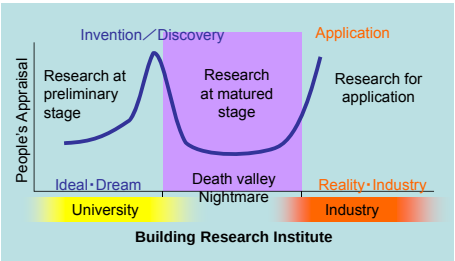
Contents of This Lecture

For the Future

Mechanism to Drive Innovation

Research to drive innovation



"Research to drive innovation" from basic research to commercialization (by Dr. Hiroyuki Yamanouchi, BRI, Japan)

INTRODUCTION

- **The State Key Laboratory for Disaster Reduction in Civil Engineering was founded in 1983. It includes Wind Tunnel Testing Division, Shaking Table Testing Division, and Ground Motion Instrumentation Division.**
- **The fundamental research in this Lab. is generally combined with large engineering application and aimed at the design code developments of local and national.**

INTRODUCTION (cont.)

Research groups in Earthquake Engineering

- Building structures (concrete and composite, high-rise buildings)
- Building structures (steel and composite)
- Bridge structures
- Lifeline systems
- Ground motion and instrumentation
- Laboratory divisions

1 Study on Seismic Behavior and Design Methods of Complex Tall Buildings

1.1 Research needs for Seismic Design of Complex Tall Buildings in China

- Structural height and complex layout;
- Design codes always behind engineering practice;
- New structural system --- effective, economical and easy construction;
- Different seismic zones.

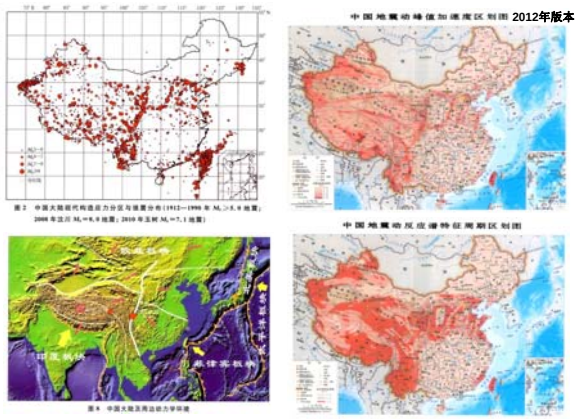
There were serious seismic damages to tall buildings in the past Earthquakes

1995 Kobe earthquake

1999 Chichi earthquake

2010 Chile earthquake

2011 New Zealand earthquake



Maximum seismic input acceleration (cm/s/s) in 3 levels and 2 stages design

Seismic intensity (~MMI)	7	8	9	Note
Level 1---stage 1	35	70	140	**Strength & deformation checking**
Level 2	100	200	400	**Detailing**
Level 3---stage 2	220 (200)	400	620	**Elasto-plastic deformation checking**

1.2 Seismic Research on Steel Reinforced Concrete Core Walls and Composite Structural Members

- In high-rise buildings the hybrid system consisting of peripheral steel frame and interior reinforced concrete (RC) core wall or steel reinforced concrete (SRC) core wall and composite members are widely used .
- A series of study on seismic behavior of SRC coupled shear walls, SRC core walls and composite members was carried out recently.

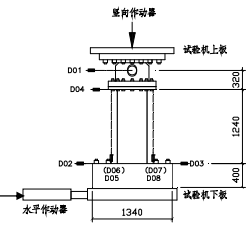
Large size SRC column tests under cyclic loading (1)

Construction of Specimens (500 x 500 mm cross-section)

Encased steels produced by professional steel structure company.

Large size SRC column tests under cyclic loading (2)

Test Set Up

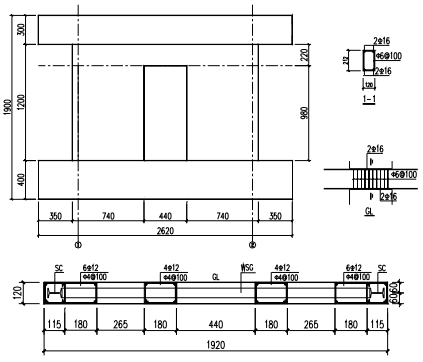


Test Results --- failure patterns

Drift = 1/50

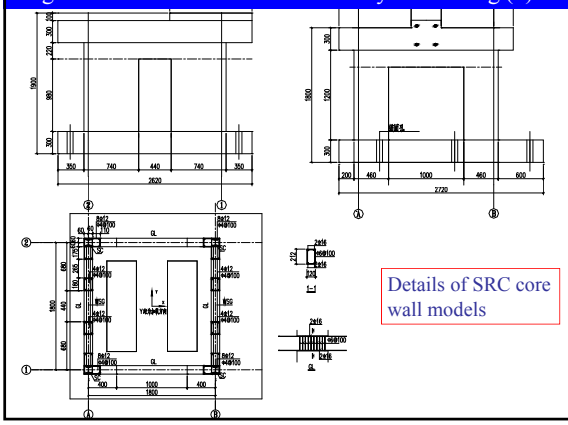
Drift = 1/30

Large size SRC shear wall tests under cyclic loading (1)



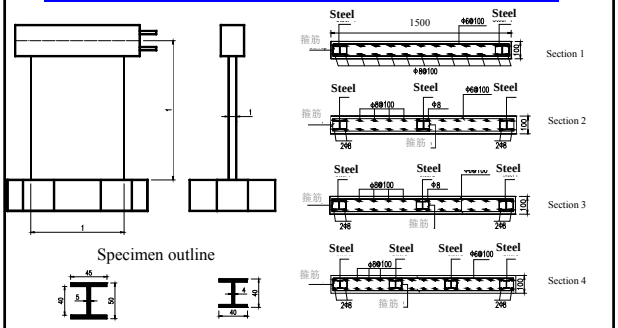
Details of SRC coupled shear wall models

Large size SRC core wall tests under cyclic loading (1)



Details of SRC core wall models

Test on SRC walls with different steel arrangement (1)



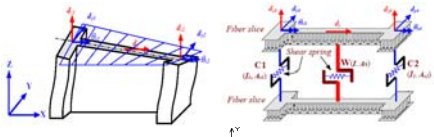
Specimen outline

Test on SRC walls with different steel arrangement (2)

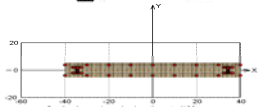
Reinforcement details | Steel placement | Specimens

SPRC wall specimens | Failure pattern of SPRC walls

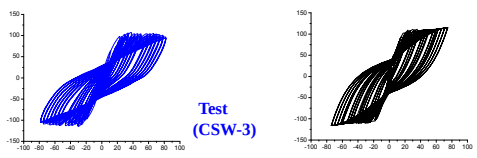
Analytical model for SRC wall piers



Simulation model of whole wall



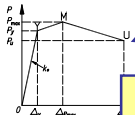
Simulation model of section



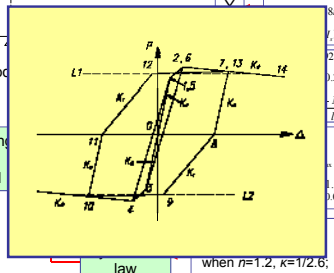
Test (CSW-3) | Simulation (CSW-3)

Analytical model of SRC column for numerical simulation of overall structure

When three characteristic points : Y , M , U are determined, the skeleton curve can be established.



Skeleton mod



Restoring force model

law

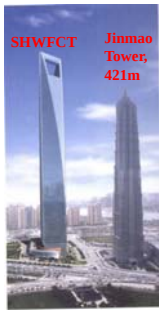
when n=1.2, κ=1/2.6;
when 0.5<n<1.2, Linear interpolation shall be used.

1.3 Shaking Table Testing on Various Complex Tall Buildings and Towers

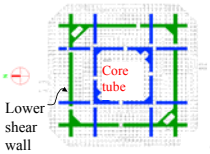
- Shaking table model test has been considered an economical, accurate, and practical way to evaluate the overall seismic performance of structures.
- To ensure that the model behaves in a similar manner as the prototype, the model designed should meet the requirements of dynamic similitude theory.
- We have done more than 50 real tall building model tests in TJ shaking table.

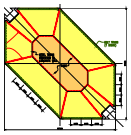
Various Model test on whole structural system

Typical Example 1: Shanghai World Financial Center Tower (SHWFCT)

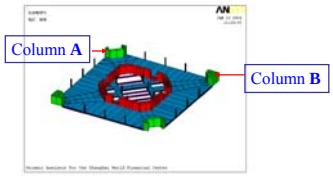


The elevation view, 492m

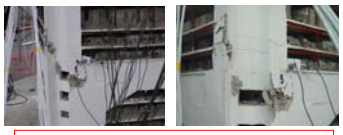




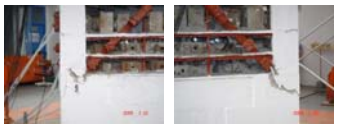
Outrigger in 91th floor



Shaking table model Test Results

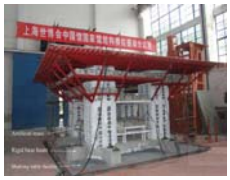


Failures of Mega-column A at floor levels from 5 to 7



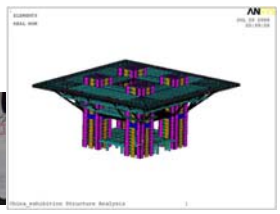
Failures of Mega-column B at 5th floor level

Typical Example 2: National Hall of China Pavilion for Expo 2010 Shanghai

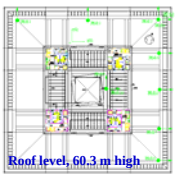


Structural layout and the torsional response can not meet design codes by analysis.

1/27 scale model test
Site vibration measurement



Ambient vibration survey on the China National Hall (2009.9)



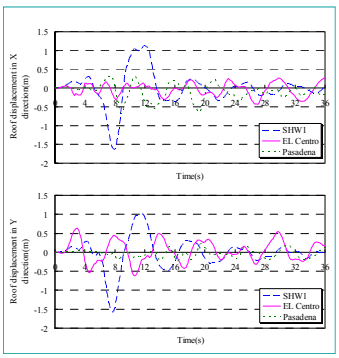
Structural Dynamic Characteristics

Method	Site Measurement		Finite Element Analysis		Shaking Table Test	
Mode	Frequency / Hz	Mode Shape	Frequency / Hz	Mode Shape	Frequency / Hz	Mode Shape
1	0.9082	Translation in *X*	0.7361	Torsion	0.883	Torsion
2	0.9180	Translation in *Y*	0.8806	Translation in *Y*	1.027	Translation in *Y*
3	0.9326	Torsion	0.8849	Translation in *X*	1.028	Translation in *X*

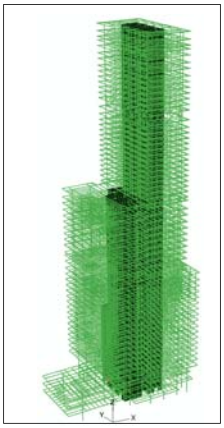
Typical example 3:
Jiali centre south tower Shanghai

Height exceeding code limit, 260 m
Setbacks in Elevation exceeding code limit
Strengthened stories
Complex structure

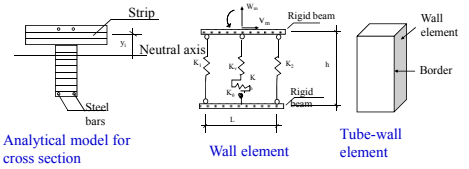
Shaking table model test
1/35 scale model, 2008.8
Elaborate finite element analysis
-ANSYS, ABAQUS

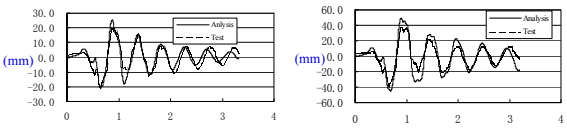


Elasto-plastic response of roof displacement
(a) in *X* direction; (b) in *Y* direction



Simplified nonlinear Dynamic Analysis for complex high-rise structures





Top floor displacement in direction of X & Y axis,
Shanghai World Financial Center Model

1.4 Output of the above research

- Design guidelines for high-rise buildings beyond the limitations in current design codes, approved by Shanghai Government, effective as of January 2005. 2nd Edition, September 2009.
- Contents: Procedure for performance-based seismic design; conceptual design, analytical model, analytical methods, detailed design measures, experiment requirements, nonlinear restoring force models for members, ect.

Table 1: Seismic performance objectives for code-exceeding tall buildings

Seismic protection category		Seismic performance level		
		Frequent earthquake	Basic earthquake	Rare earthquake
A		Fully operational	Fully operational	Operational
B		Fully operational	Operational	Life safety
C	Buildings with height exceeding code limit and regular RC structure	Fully operational	Repairable	Life safety
	Buildings except above	Fully operational	Operational	Life safety

2. Study on Structural Passive Control Technology with Application in Tall Buildings

2.1 Damper bracing system for tall buildings

2.2 Combined isolation system for tall buildings

2.3 Adjacent buildings connected by dampers to reduce seismic response

2.4 TMD study with application to tall buildings

2.5 Shaking Table Model Test of TMD Controlled Structure Resting on Pile-foundation

2.6 Studies of particle damper system

2.1 Combined energy dissipation bracing system for tall buildings

- **Features:**

1) combined actions by rubber bearing and oil damper;
2) dissipating seismic energy in different level of earthquake: smaller quake by rubber bearing large quake by oil damper;
3) easy to construct.

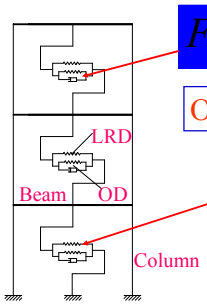
- shaking table testing
- numerical analysis

Steel frame model with dampers on shaking table in testing

Shaking table model test of R.C. frames with or without dampers

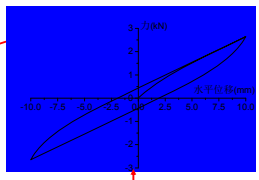
Test results summary

- **The oil damper can not only provide damping but also stiffness to the structural system.**
- **The combined system can reduce seismic response significantly.**
- **The analytical model for this system is developed, and optimal analysis is conducted for the design parameters of the system.**



$$F(x,\dot{x}) = c_d\dot{x} + k_d x$$

Oil damper simulation



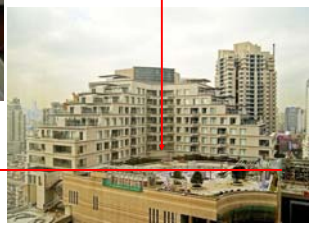
Analytical model

Rubber bearing Simulation

Application (1)

To add more stories on an existing R. C. frame building with 88 dampers and braces --- Shanghai Gateway Plaza

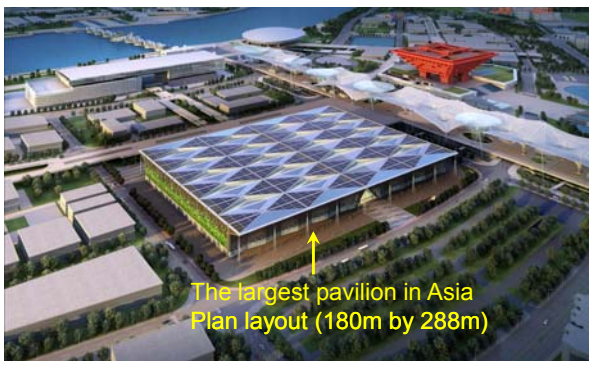
Adding 8 stories above 10



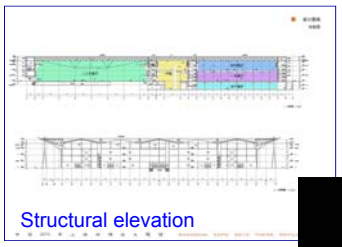
Existing level 10-story

Application (2)

2010 Shanghai-Expo Theme Pavilion

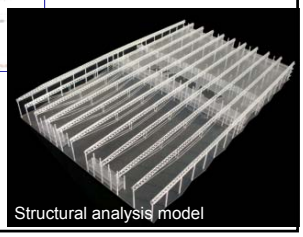


Description of the structure



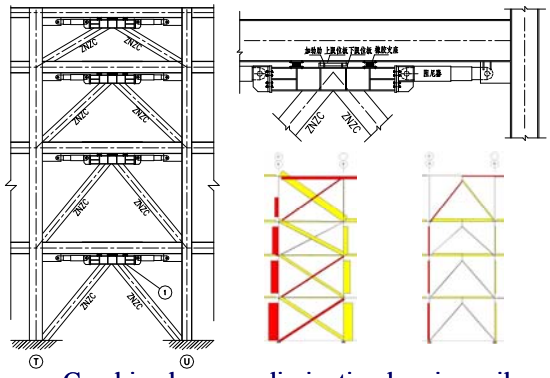
Structural elevation

- The structure in Y direction is unsymmetrical.
- Torsional response is too large (T3/T1 and T3/T2) if moment steel frame is only used.



Structural analysis model

- Largest exhibition building in Asia with different story height.
- Temperature induced stress is too large if rigidly braced steel frame is used.



Combined energy dissipation bracing, oil damper and LRB

The construction site photos (2008-11-10)

2.2 Combined isolation system for tall buildings

- The combined isolation system is composed of rubber bearings to restore position, and frictional sliding bearings to carry on vertical load and to dissipate seismic energy as well. The system is suitable for tall buildings
- To verify the effectiveness of this system, a 1/12-scale and three-story steel frame model was tested on shaking table with base fixed (FIX) and isolated (SLD) separately for comparison.

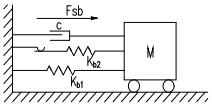
Test results summary

- The effectiveness of sliding isolators is enhanced by adding rubber bearings and thereby to reduce the residual displacements to manageable levels.

The isolation system has good re-centering capability under different input level with a small residual displacement.

The vertical component of the ground motion has significant effect on the axial loads, and tension may occur in rubber bearings.

Restoring force model for sliding bearing



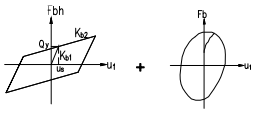
$$F_{sb} = F_{sbh} + F_{sb\xi}$$

Before sliding:

$$F_{sbh} = (k_{b1} - k_{b2})(u_1 - u_s) + k_{b2} \cdot u_1 = k_{b1}u_1 - (k_{b1} - k_{b2})u_s$$

During sliding:

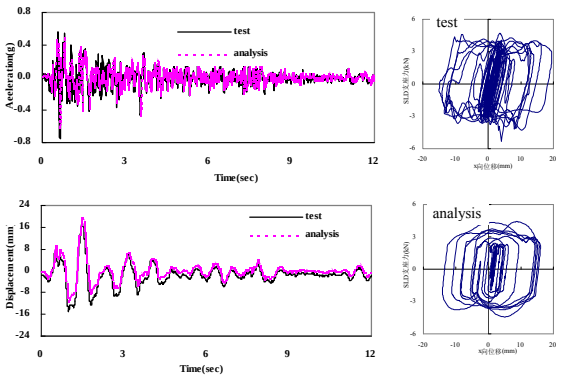
$$F_{sbh} = K_{b2}u_1 + Q\,\mathrm{sgn}(\dot{u}_1)$$



$$F_{sb\xi} = c_b \cdot \dot{u}_1$$

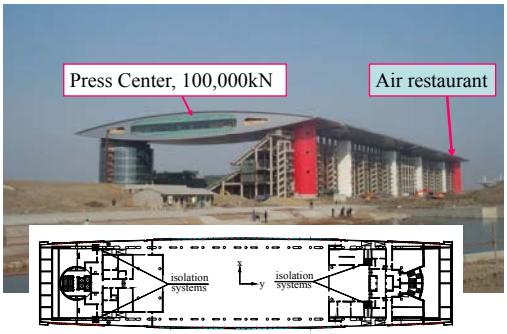
F_{sbh} **Coulomb restoring force of sliding**

$F_{sb\xi}$ **Viscous restoring force of sliding**

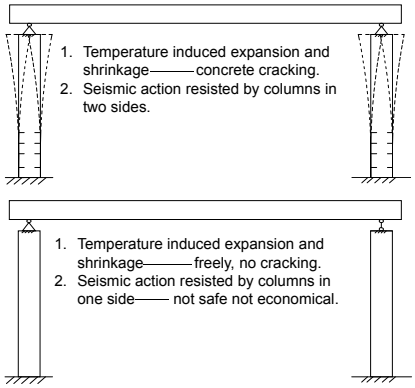


Comparison of the test and analysis (time history and loops)

Application 1: Shanghai F1 Press Center and Air Restaurant, 32m, 2004.8



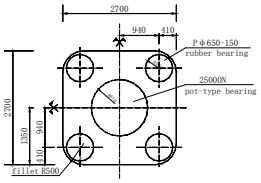
The difficulties in structural design



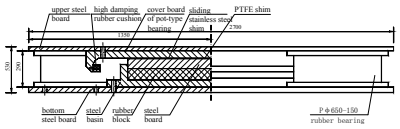
1. Temperature induced expansion and shrinkage——concrete cracking.
2. Seismic action resisted by columns in two sides.

1. Temperature induced expansion and shrinkage——freely, no cracking.
2. Seismic action resisted by columns in one side—— not safe not economical.

In order to reduce seismic action and temperature-induced stress, combined use of slider bearing and rubber bearings were adopted.



Plan layout of the bearings in one column



Cross section of the bearings

The bearings placed On the top of the Mega-column

40 bearings (8 sliders and 32 rubber bearings) installed on the top of 8 mega-size columns with the height of about 30 meters.

2.3 Study on Adjacent Buildings Connected by Oil (viscous) Dampers

Overpass between two buildings collapsed during Kobe earthquake of 1995

Shaking table tests

•Three connection conditions between the two frames were involved: connected by rigid steel rods, connected by oil dampers, or without any connections.

Adjacent structures linked by oil dampers in testing

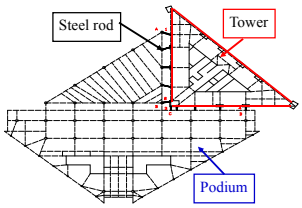
Test and analysis results

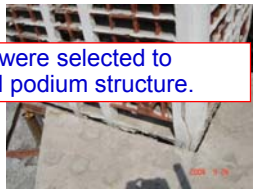
- The test results show that the modal damping ratios of both buildings could be increased significantly and so their seismic responses could be reduced effectively if appropriate parameters for the oil dampers were selected.
- Analysis shows that (1) this control method is quite robustness to different ground motions; and (2) if vibration frequencies of the two connected structures are far apart, the vibration control effect is much better.

One Application Example

- This concept was applied to a 60-story ultra-tall building (333 m) with 10-story large podium (49.6 m) connected by oil dampers to reduce their torsional seismic response.
- Designer: ECADI

- The structural problem
- The stiffness center of podium is far apart from the mass center, and the deformation of the podium can not meet the requirements of current design codes.

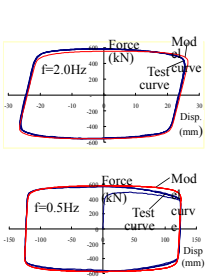




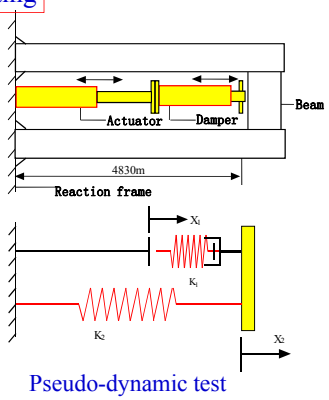
•Therefore the oil dampers were selected to connect the main tower and podium structure.

Design Parameters
Damper: 40 pieces
α= 0.15
C=250
Damping force: 500kN, 600kN
Locations of the dampers: floor levels on and below the roof of podium structures (7th floor to 10th floor).

Damper behavior testing

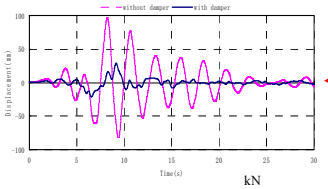


Tested and simulated curves



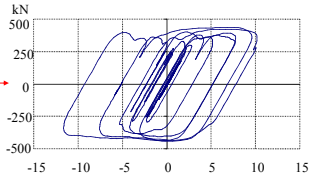
Pseudo-dynamic test

Calculating result under frequently occurred earthquake (42 gal)

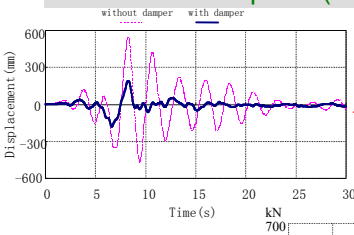


X direction displacement history of point A on 7th floor of podium with and without dampers

Hysteresis curve of viscous force vs. displacement of damper 2 on the 10th floor under frequently occurred earthquake

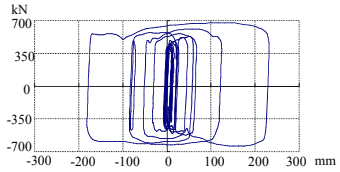


Calculating result under seldom occurred earthquake (220 gal)



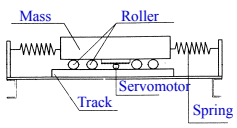
X direction displacement history of point A on 7th floor of podium with and without dampers

Hysteresis curve of viscous force vs. displacement of damper 2 on the 10th floor under seldom occurred earthquake



Damper installation at the construction site

2.4 Vibration control study on tall buildings using TMD



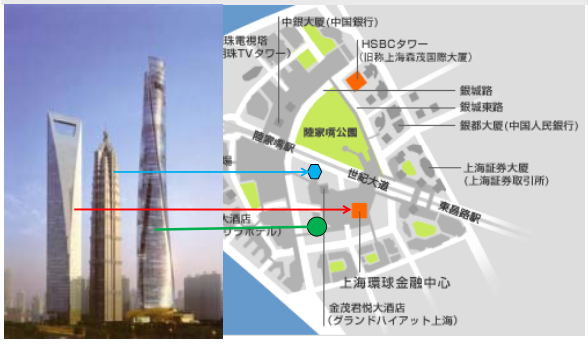
- **Shaking table tests were carried out on a 3-story steel frame structure equipped with this system under various seismic inputs.**

3-story steel frame model in testing

Test results show

- **The earthquake responses of the structure were reduced significantly.**
- **The damping value and the characteristics of frequency spectrum of the seismic input had a significant effect on the control efficiency of this system.**
- **The analytical model is developed for the tested structure, and the calculation results agree well with the test results.**

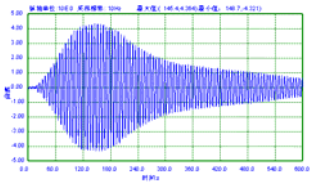
(1) Application to Shanghai World Financial Center Tower

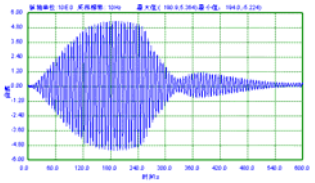


Stories: 101 floors
Height: 492m
Location of the vibration control devices: 394m (Floor 90)
Vibration period:
6.3s (Y direction)
6.0s (X direction)
2.2s (Torsion)
Damping ratio: 1% (wind), 4% (earthquake)
Moving mass: 150 t/set
Amplitude of moving mass: ±1.1m
Completion date: May 30, 2008

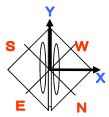
Damper locations in 90th floor

Device adjustment and inspection photos in construction site, May 1, 2008

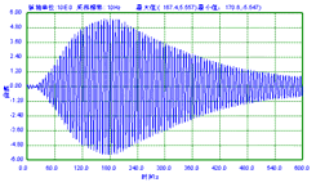


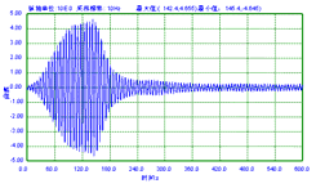


Structural response attenuation with ATMD OFF
（damping ratio: 0.422%）
(Y direc.) Ty=6.502 sec.

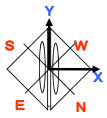


Structural response attenuation with ATMD ON
（damping ration 3.404%）
(Y direc.)
Ty=6.502 sec.





Structural response attenuation with ATMD OFF
（damping ratio: 0. 459 %）
(X direc.) Tx=6.398 sec.



Structural response attenuation with ATMD ON
（damping ratio: 3.865%）
(X direc.) Tx=6.398 sec.

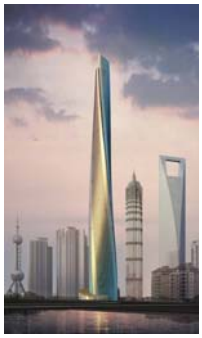
Field measured and calculated dynamic properties of the structure

Direction	Excitation	Frequency (Hz)	Period (s)	Damping ratio (%)
Y	excitation at 90 floor (ATMD off)	0.1538	6.502	0.422
	excitation at 90 floor (ATMD on)	0.1538	6.502	3.404
	Ambient vibration	0.1538	6.502	0.592
	Calculated dynamic properties	0.1534	6.5166	----
X	excitation at 90 floor (ATMD off)	0.1563	6.398	0.459
	excitation at 90 floor (ATMD on)	0.1563	6.398	3.865
	Ambient vibration	0.1563	6.398	0.890
	Calculated dynamic properties	0.1551	6.4469	----

Vibration control using ATMD and site measurements on the Shanghai World Financial Center Tower, Xilin Lu, Peizhen Li, Xianqun Guo, Weixing Shi and Jie Liu, ***Struct. Design Tall Spec. Build.,*** 23, 105–123 (2014).

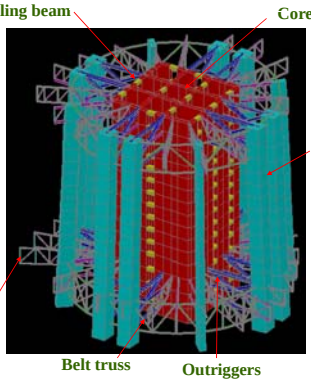
（2） TMD design for wind resistance of Shanghai Tower

Building height----632 m
– Structural height----574.6 m
– Floor number----above ground 124 floors, under ground 5 floors
– Total floor area---- 573,000 m^2
– Main functions
Office
Hotel
Shops
Sight seeing

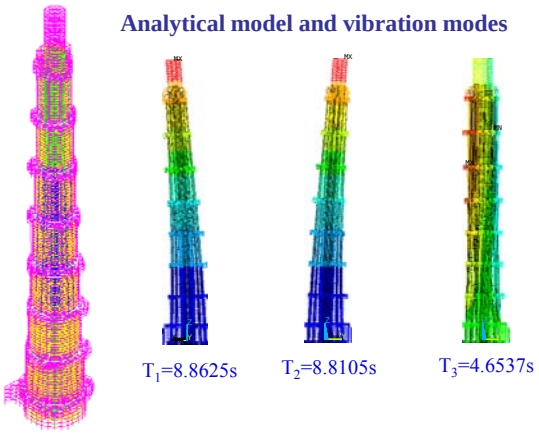


Structural systems

Core wall
+Mega-column
+Outriggers
+Belt truss
+Radial truss



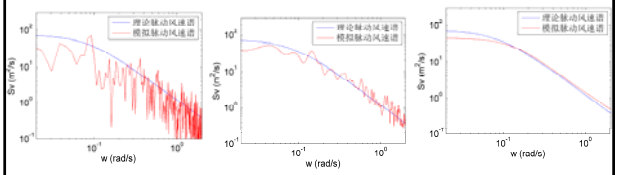
Analytical model and vibration modes



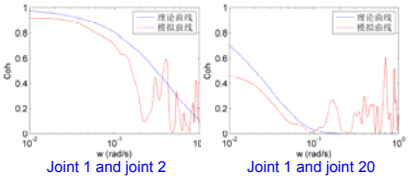
Model test on shaking table at Tongji（1/50 scale, 2010.7.30）

TMD design under wind loading for SH Tower

Wind spectrum by different creation methods



Wind spectrum coherence at different joints under one year return period



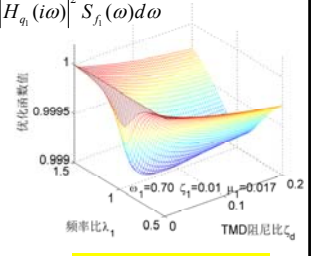
TMD parameter optimization

No control displacement $(\sigma_{x_k}^0)^2 = \varphi_{k1}^2 \int_{-\infty}^{+\infty} \left|H_{q_1}^0(i\omega)\right|^2 S_{f_1}(\omega) d\omega$

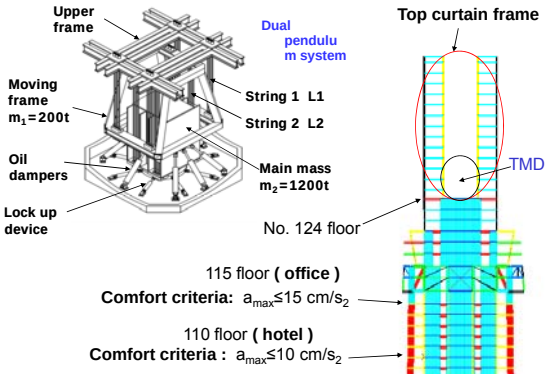
TMD control displacement $(\sigma_{x_k})^2 = \varphi_{k1}^2 \int_{-\infty}^{+\infty} \left|H_{q_1}(i\omega)\right|^2 S_{f_1}(\omega) d\omega$

Vibration reduction factor $\delta_{x_k}^2 = \dfrac{(\sigma_{x_k})^2}{(\sigma_{x_k}^0)^2}$

Through nonlinear optimization (MATLAB)



Optimization results



TMD structure demonstration (by RWDI)

TMD parameters

- Location: 124 floor level
- Height: 573.9 m
- Moving mass: 1400 t (200t frame + main mass)
- Mass ratio: $\mu_x = \mu_y = 1.72\%$
- Stiffness: $k_x = 683.68 kN/m$ $k_y = 692.93 kN/m$
- Damping factor: $c_x = 99.17 kN \cdot s/m$ $c_y = 115.14 kN \cdot s/m$
- String length: $L_x = 20.13m$ $L_y = 19.86m$ (~ 20m)
- Dampers : 8 oil dampers
  angle to floor: 45°
  damping coefficient: $C_{eq} = 53.58 kN \cdot s/m$

Dynamic response under wind load (1)

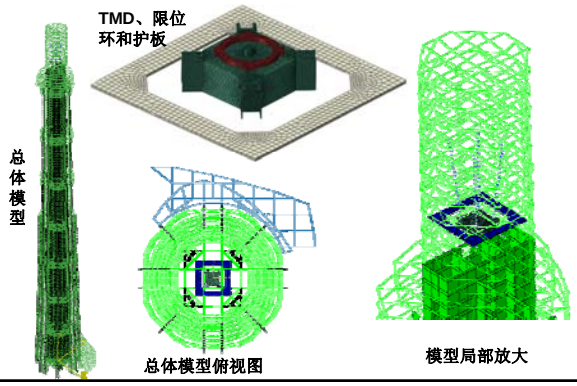
maximum acceleration (Y direction)

Pulse wind RP	floor	acceleration (cm/s^2)	
		No TMD	With TMD
1 year RP (wind speed: 25.8m/sec.)	115	6.5	2.7
	110	6.3	2.4
10 years RP (wind speed: 36.3m/sec.)	115	11.4	6.2
	110	10.3	5.6

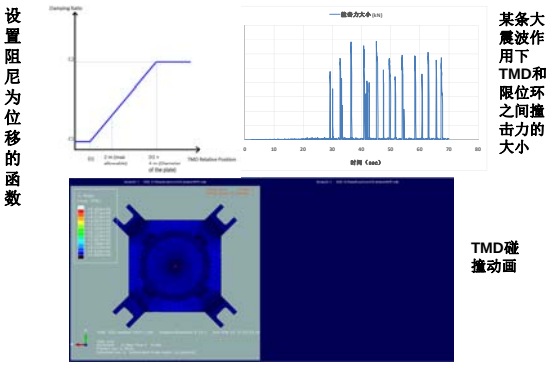
已确定在实际工程中应用TMD (1000 t)电涡流阻尼系统（2013.8）。

中试阶段：悬吊高度：22米，质量25吨，TMD周期约10秒，阻尼比7~20%

上海中心电涡流TMD计算审核(委托项目)

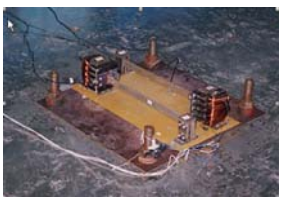


上海中心电涡流TMD计算审核



2.5 Shaking Table Model Test of TMD Controlled Structure Resting on Pile-foundation

Shaking table test on soil-pile-structure-TMD interaction system



TMD based on electromagnetic whirlpool energy consumption

Due to the strong interaction between the structure and the soil, the efficiency of the TMD system decreases drastically, and the soil-structure interaction should be taken into consideration when designing the TMD system.

Shaking table model test for a steel structure under control of tuned liquid damper

tuned liquid damper (TLD)

Shaking table test on soil-pile-structure-TLD interaction system

Test results shows that the TLD efficiencies decrease when the SSI effect is considered. The frequency feature and the intensity of the input seismic motion have important influence on this reduction. Therefore, the site soil condition and input seismic motion should be considered in the TLD design when the controlled structure is built on the soft soil.

2.6 Studies of particle damper system

Concept of particle damper

Particle dampers are simple and efficient passive devices that are used to attenuate the vibrations of lightly damped structures, through the impacts between solid particles and the primary system. They are widely used in aerospace and mechanical engineering (such as turbine blades, rocket engine turbo-pumps). The application in civil engineering is at the beginning stage: chimney, high-rise building and cable-stayed bridge pylon.

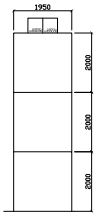
Attributes of particle damper

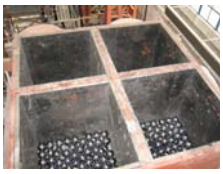
Advantages: ruggedness, reliability, insensitivity to the extreme environments (such as high vacuum, high temperatures, cryogenic temperatures, and corrosive environments).
Disadvantages: noise and impulse at the impacts, highly nonlinear behavior and no guidelines for optimum design procedure.

Response of high-rise building with particle damper system under strong ground motion

Parque Araucano building performed very well during 2010 Chile earthquake and the building did not suffer any damages above the ground or at any of the six subterranean floors and basement walls.

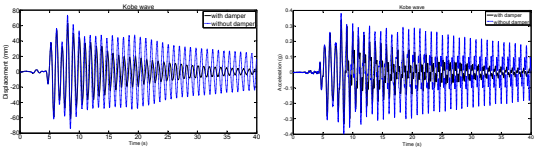
Shaking table tests of three-storey steel frame with particle damper system





Particle damper can effectively attenuate the response of lightly-damped primary system with a small weight penalty (2.25%). The reduction of the r.m.s response is even better, which means particle damper can dissipate a lot of input seismic energy.

Controlling attributes of particle damper system:



The responses of the controlled and uncontrolled system are the same at the very beginning time period, after a while, the controlled curve begins to decay quickly. This is a similar phenomenon encountered in the operation of Tuned Mass Damper. The vibration reduction effect is not good at the very beginning and becomes better as time goes by. The reason is that it takes some time for particles to impact with the wall of the container. After certain impacts, the particle damper system starts to dissipate the input energy by momentum transfer.

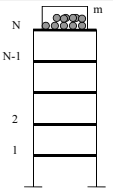
Theoretical analysis of particle damper system

Primary system

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F} + \mathbf{E}\ddot{x}_g$$

$\mathbf{F} = [0 \;\; 0 \;\; \ldots \;\; F_N]^T$ Contact force between particles and the primary system

Particles



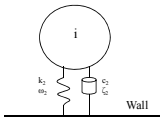
Contact force model (Linear):

$$F_{ij}^n = \begin{cases} k_2\delta_n + 2\zeta_2\sqrt{mk_2}\dot{\delta}_n, & \delta_n = r_i - \Delta_i \quad (particle - container) \\ k_3\delta_n + 2\zeta_3\sqrt{\dfrac{m_i m_j}{m_i + m_j}k_3}\dot{\delta}_n, & \delta_n = r_i + r_j - |\mathbf{p}_j - \mathbf{p}_i| \quad (particle - particle) \end{cases}$$

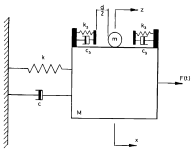
$$F_{ij}^t = -\mu_s F_{ij}^n \dot{\delta}_t / |\dot{\delta}_t|$$

Governing equation:

$$m_i\ddot{\mathbf{p}}_i = m_i\mathbf{g} + \sum_{j=1}^{k_i}(\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^t), \quad \mathbf{I}_i\ddot{\boldsymbol{\Phi}}_i = \sum_{j=1}^{k_i}\mathbf{T}_{ij}$$

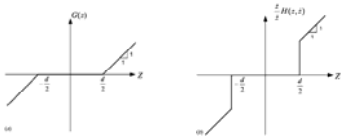


Specifically, for single particle damper under simple excitation case, it can be obtained **analytical solutions**. For more than one particle case, there is only numerical solutions.



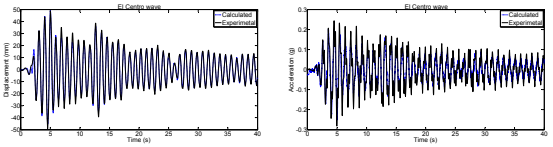
$$\ddot{x} = -2\zeta\omega_n\dot{x} - \omega_n^2 x + \frac{f(t)}{M} + \sum_{k=1}^{N}(\mu_k[\omega_2^2 G(z_k) + 2\zeta_2\omega_2 H(z_k,\dot{z}_k) + \mu_s g\,\mathrm{sgn}(\dot{z}_k)])$$

$$\ddot{z}_k = -\ddot{x} - [\omega_2^2 G(z_k) + 2\zeta_2\omega_2 H(z_k,\dot{z}_k) + \mu_s g\,\mathrm{sgn}(\dot{z}_k)],\ k = 1,2,...,N$$



x: displacement of the primary system
Z_k : displacement of the particle relative to the container
G(z): nonlinear spring force function
H(z,z): nonlinear damper force function

Calculated curve agrees well with the experimental curve

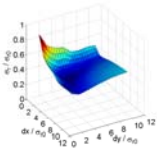


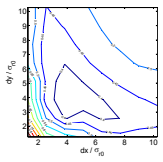
Parametric study:

The following quantities provide good "illumination" of the underlying physical phenomena occurring among the system components in the optimum performance: (1) the Effective Momentum Exchange, (2) the amount of internal energy dissipation due to impact and friction, and (3) the cross-correlation of the velocity of random particles.

When the system is obtained the optimum control effect (the response is the minimum), the dissipated energy and effective momentum exchange value is the maximum.

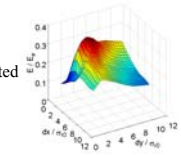
(a) System response

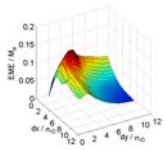




(b) Contour plot of the response

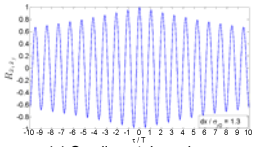
(c) Dissipated energy



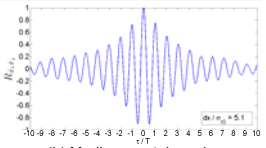


(d) Effective Momentum Exchange

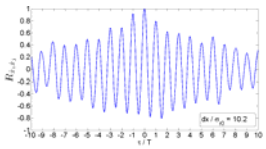
The velocity correlation function of random particles decays much faster in the optimum operating range than that in the inefficient operating range.



(a) Small container size



(b) Medium container size (in the optimum range)



(c) Large container size

To be Continued