2011 PEER Annual Meeting

Study on Seismic Performance and Passive Control Technology for Tall Buildings with Application

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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 (From J. of SDT&SB)

2011 New Zealand earthquake

Design Practice for Code-exceeding tall buildings in China

Most tall buildings are designed according to design codes.

There is a permission to design code-exceeding buildings which need reviewed by a committee.

Categories of Code-exceeding Tall Buildings:

(1) Tall buildings with heights exceeding the applicable limits for the respective structure type as specified in design code.

(2) Tall buildings with three or more of plan or vertical irregularities.

The irregularities involve drastic changes in geometry, interruptions in load paths, discontinuities in both strength and stiffness, disruptions in critical regions by openings, large eccentricity between the rigidity centre and mass centre, etc. The allowable limits are specified in design codes.

(3) Tall buildings with one or more severe plan or vertical irregularities list in design codes. Sever irregularities include severely over limit of the above items, transfer floor at high floor level, multiple complex structure, etc.

(4) Other tall buildings. These are tall buildings which have new or undefined structural system in current codes, or have long spans and high occupancies such as train stations, stadiums, department stores, exhibition halls, airports, etc.

In some cases detailed study on Code-exceeding high-rise structures is required by review panel.

Detailed study may include:

1). Whole structural model test to observe the overall behavior of the structure under different levels of seismic action;

2). Detailed structural analysis for the strength design and deformation checking of members and whole structure;

3). Large size structural member or joint test to check the detailing design;

4). Performance-based seismic design procedures are sometimes required;

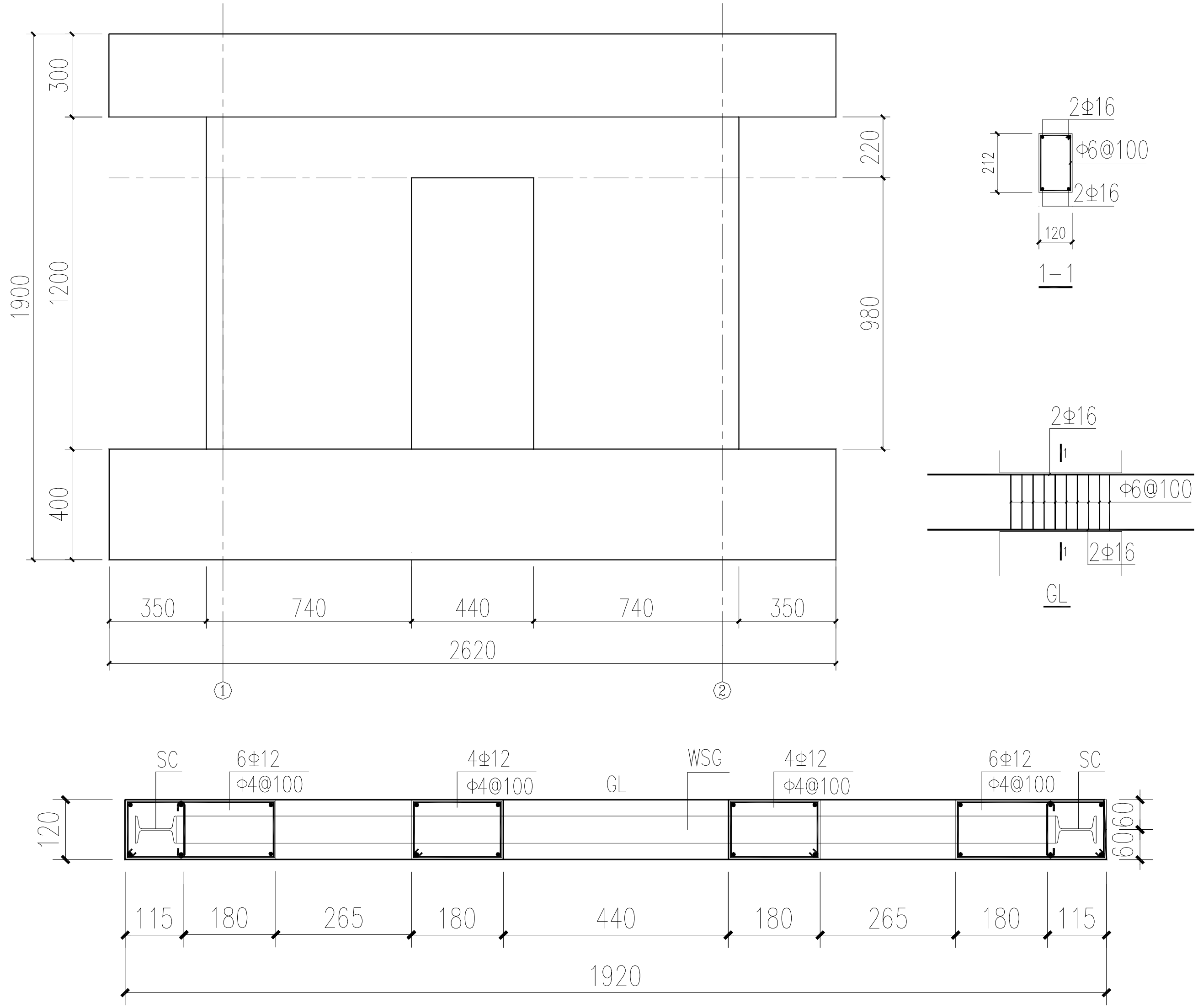
5). Advanced technology application is sometimes suggested.

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

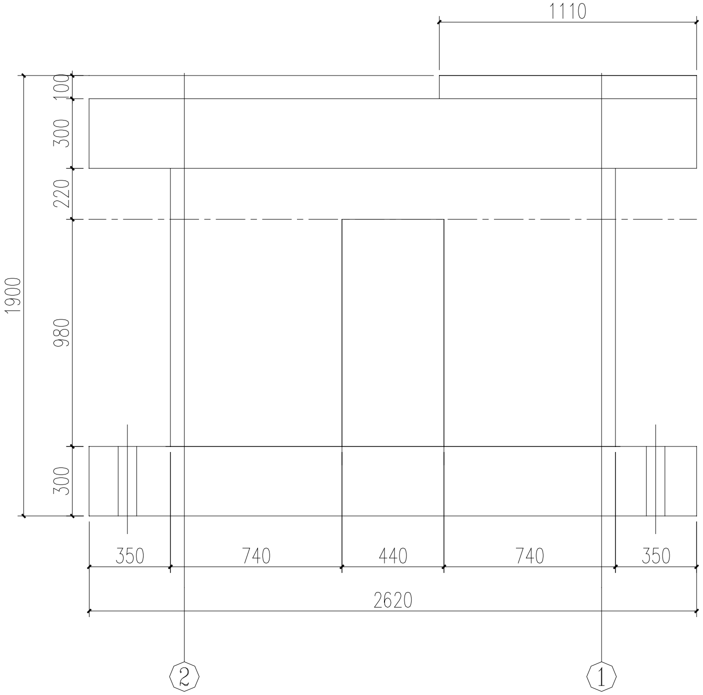
Seismic protection category		Seismic performance level		
		Frequent earthquake	Basic earthquake	Rare earthquake
A		Fully operational	Fully operational	Operational
B		Fully operational	Operational	Life safety
C	Buildings with height exceeding code limit and regular RC structure	Fully operational	Repairable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

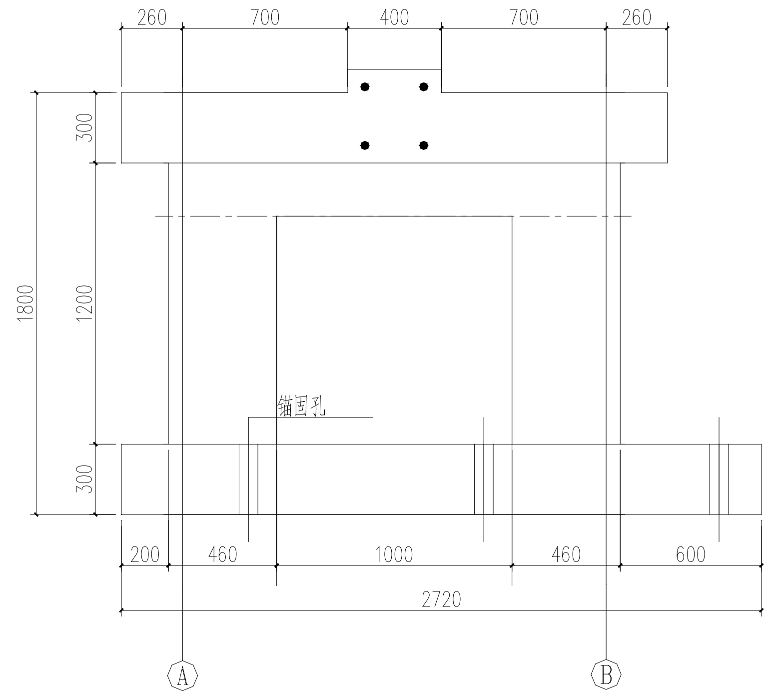
1.2 Seismic Research of Steel Reinforced Concrete Core Walls and composite structural members

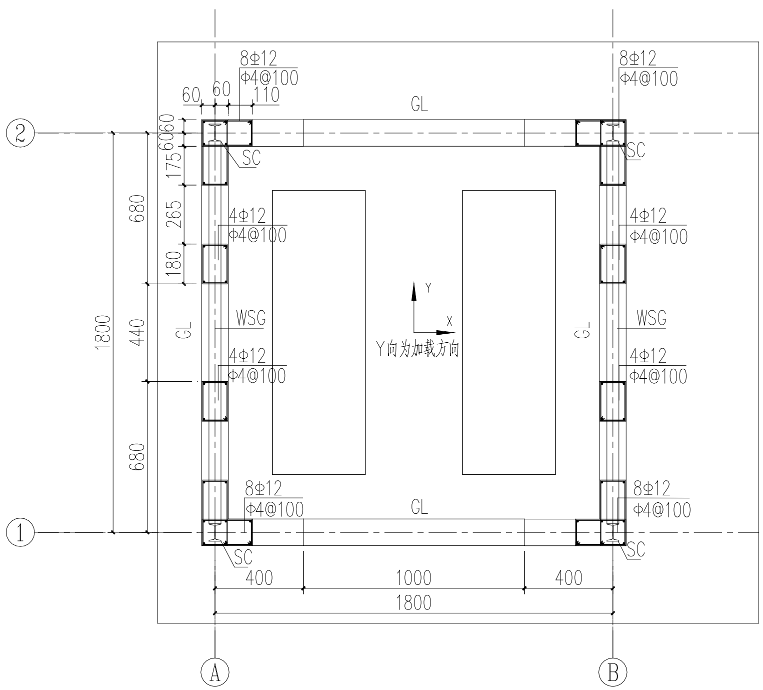
- In high-rise buildings the hybrid system consisting of peripheral steel frame and interior reinforced concrete (RC) core wall or steel reinforced concrete (SRC) core wall and composite members are widely used .
- A series of study on seismic behavior of SRC coupled shear walls, SRC core walls and composite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

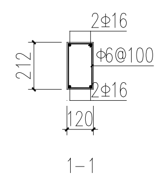


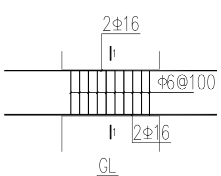
Details of SRC coupled shear wall models





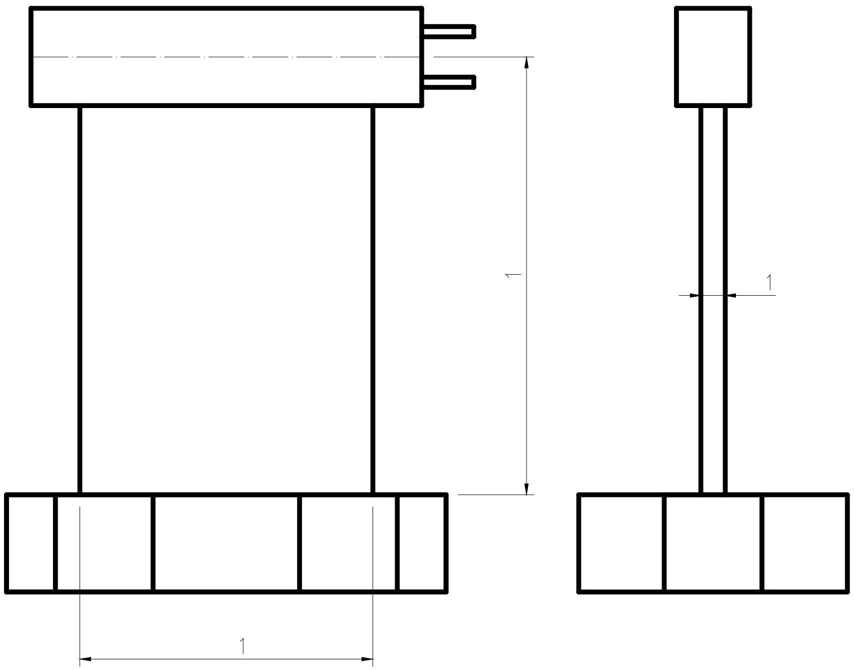




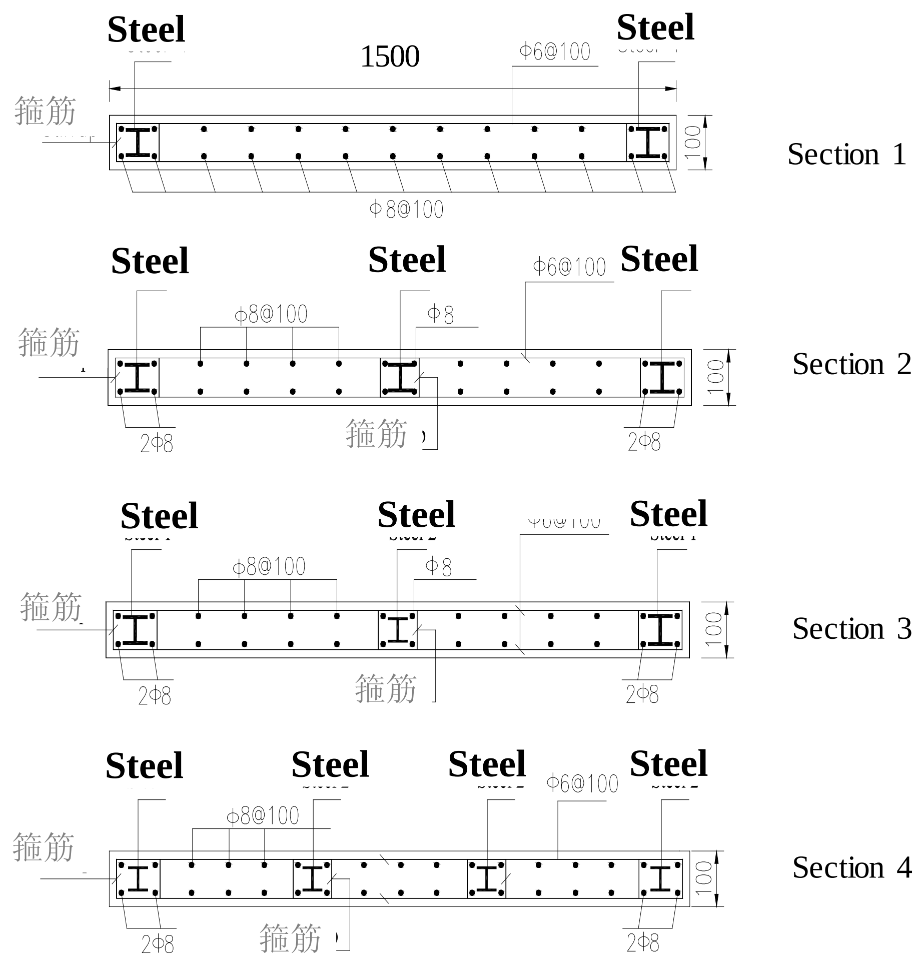


Details of SRC core wall models

Test on SRC walls with different steel arrangement



Specimen outline



Test on SRC walls with different steel arrangement

Reinforcement details

Steel placement

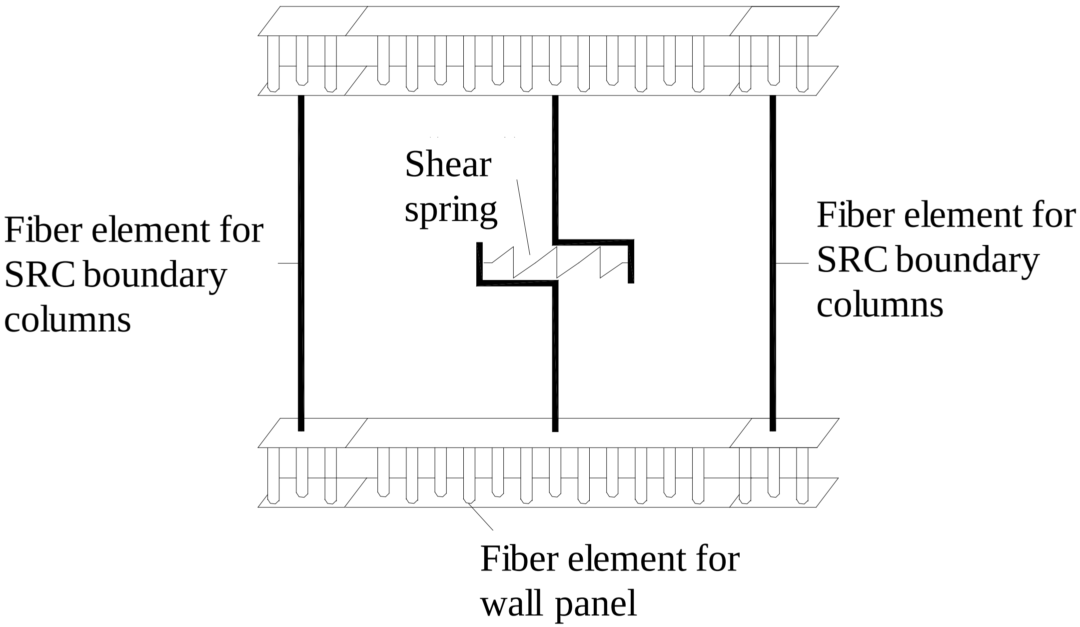
Specimens

Test on steel plate reinforced concrete (SPRC) walls

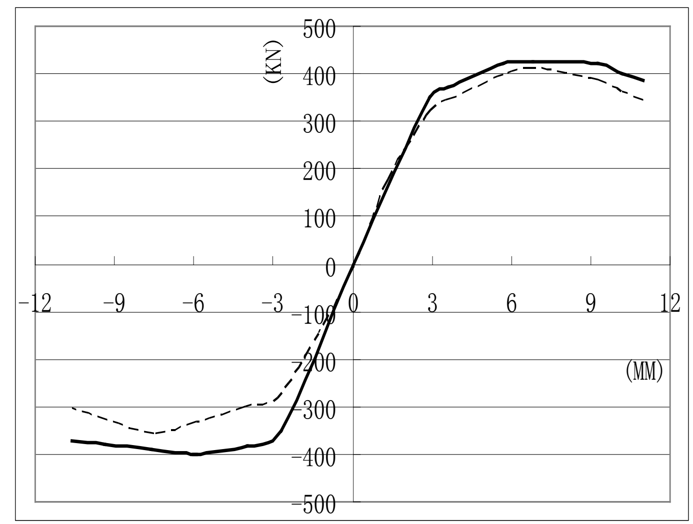
SPRC wall specimens

Failure pattern of SPRC walls

Numerical Analysis on SRC walls



Analytical model for SRC wall piers



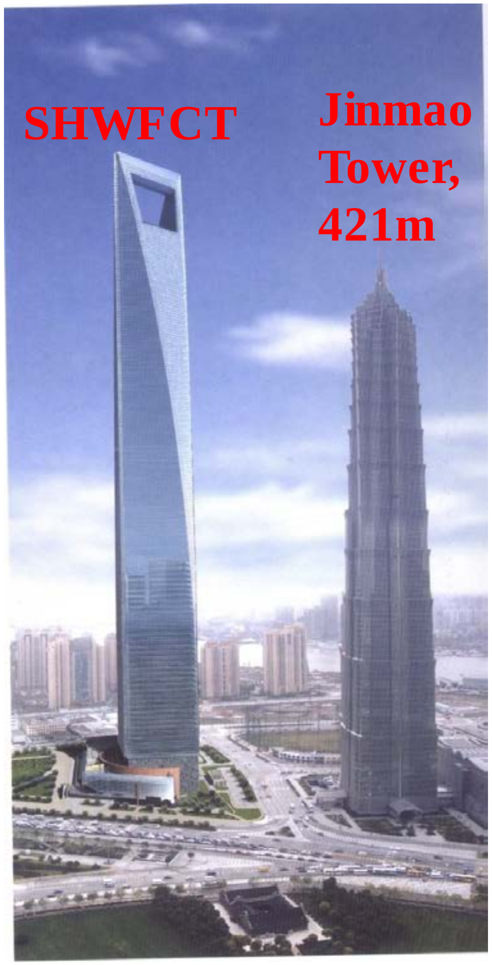
Lateral force vs. deformation skeleton curves

1.3 Shaking Table Testing on Various Complex Tall Buildings and Towers

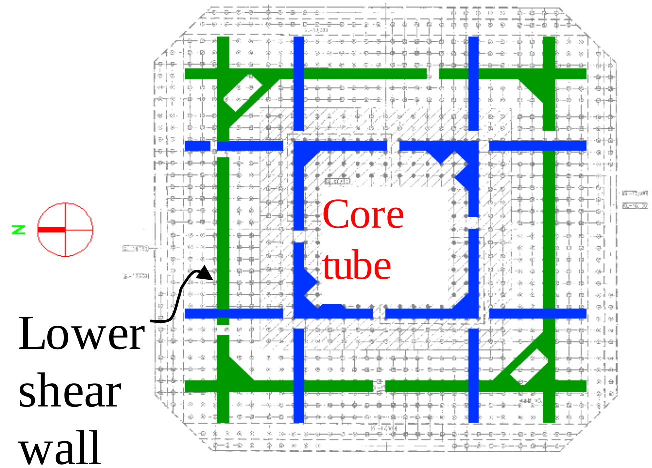
- Shaking table model test has been considered an economical, accurate, and practical way to evaluate the overall seismic performance of structures.
- To ensure that the model behaves in a similar manner as the prototype, the model designed should meet the requirements of dynamic similitude theory.
- We have done more than 40 real tall building model tests in TJ shaking table.

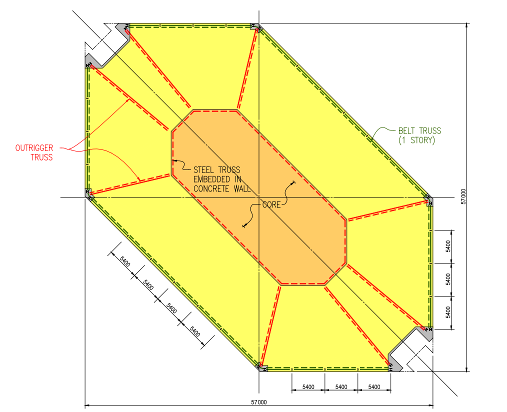
Various Model test on whole structural system

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



The elevation view, 492m





Outrigger in 91th floor

Shaking table model Test Results

There were no visible cracks after the input of frequent earthquake and basic earthquake of intensity 7.

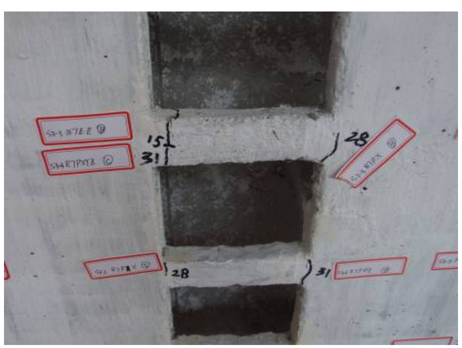
With rare earthquake of intensity 7, obvious damage was observed.

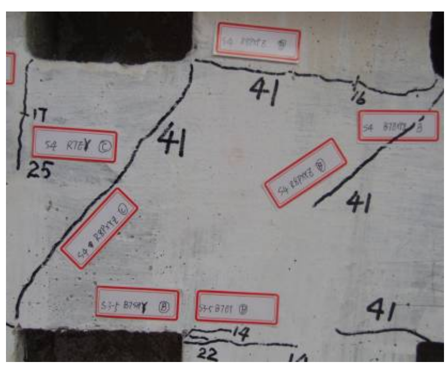
After the input of rare earthquake of Intensity 8, severe damage was observed, but the structure did not collapse.

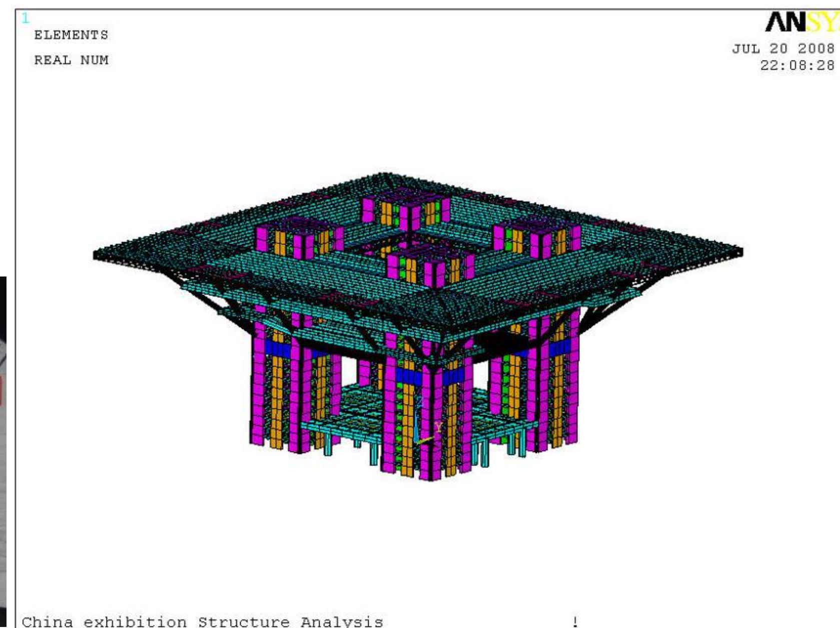
Typical Example 2: National Hall of China Pavilion for Expo 2010 Shanghai

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

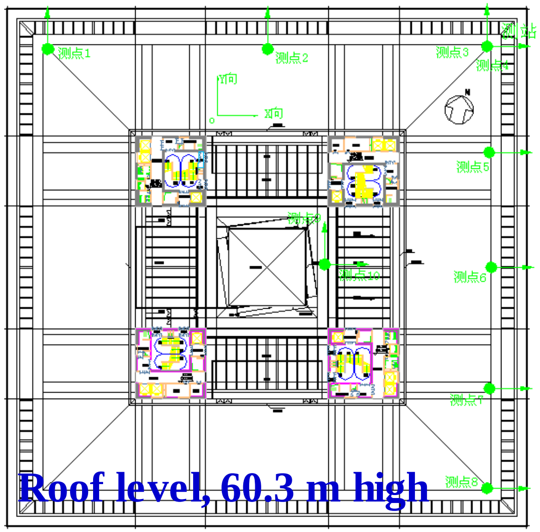
1/27 scale model test
Site vibration measurement







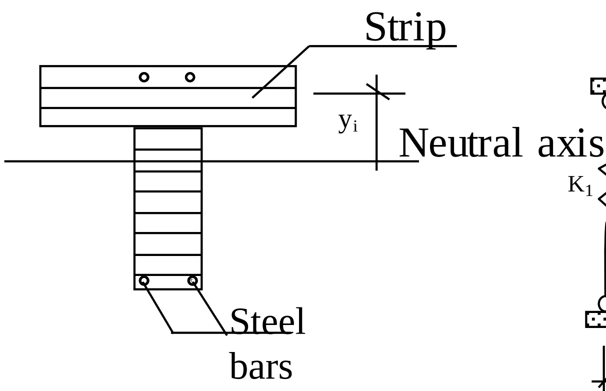
Ambient vibration survey on the China National Hall (2009.9)



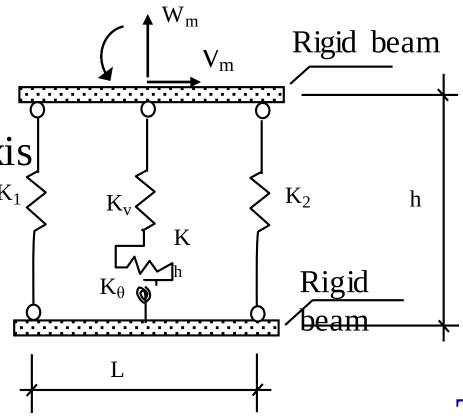
Structural Dynamic Characteristics

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*

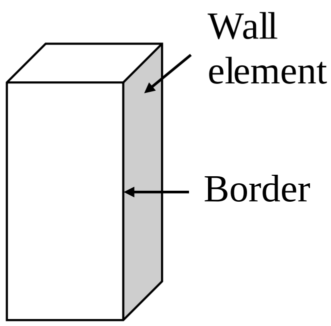
Simplified nonlinear Dynamic Analysis for complex high-rise structures



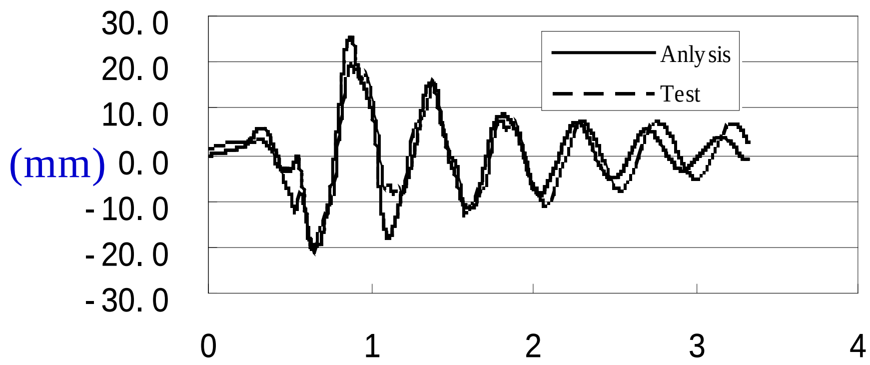
Analytical model for cross section

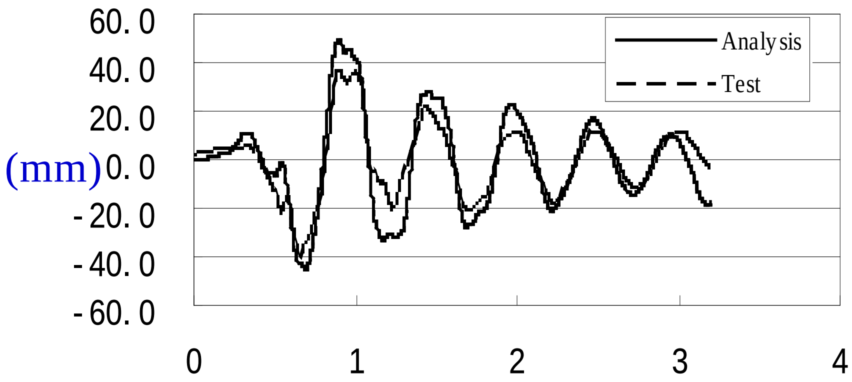


Wall element



Tube-wall element





Top floor displacement in direction of X & Y axis,

Shanghai World Financial Center Model

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, 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.

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

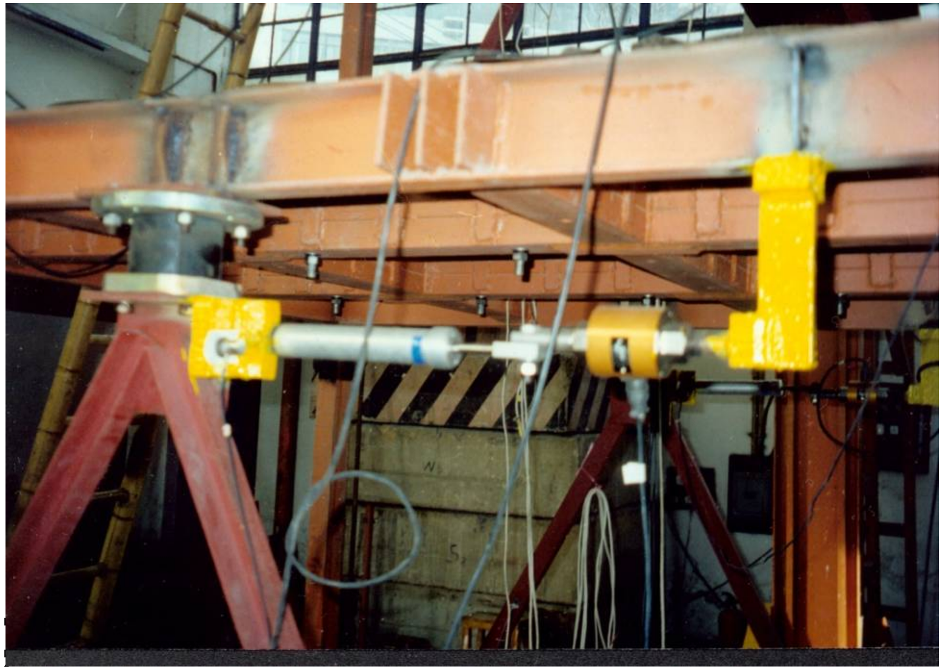
2.1 Combined energy dissipation bracing system for tall buildings

- **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

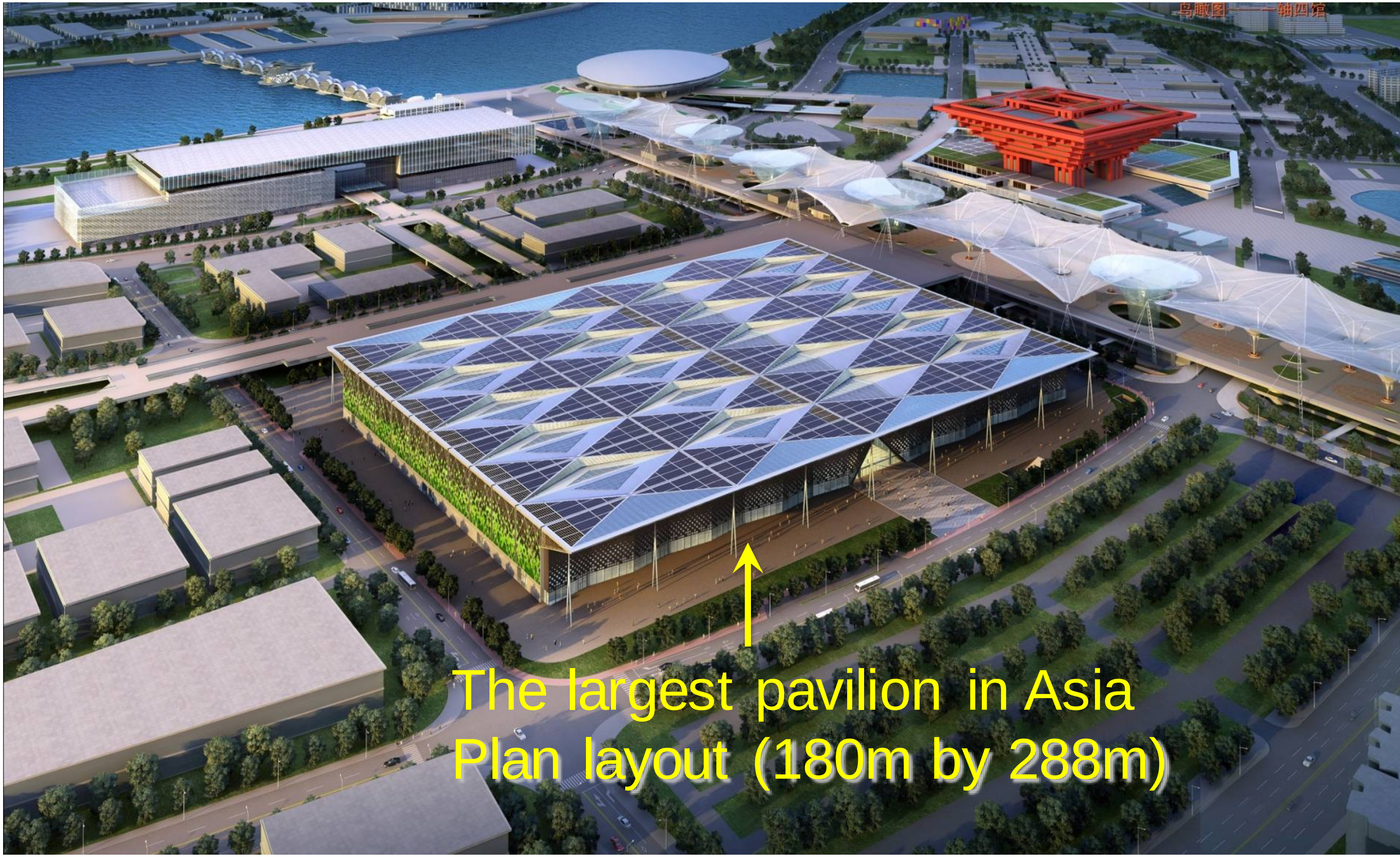
Application

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

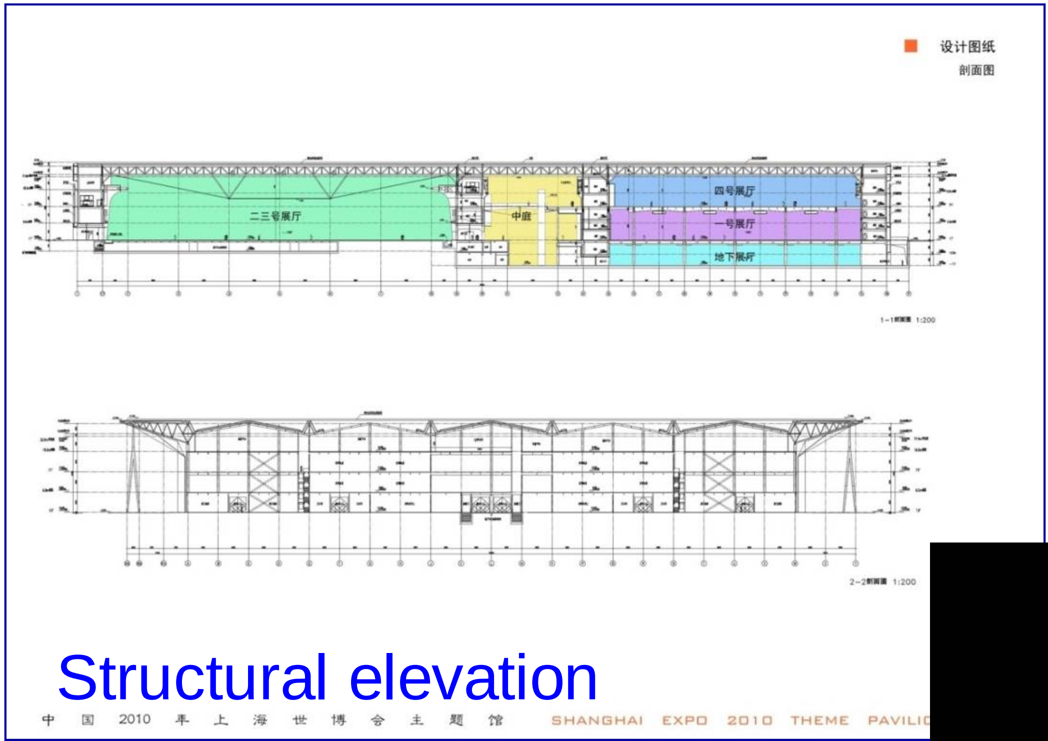
Adding 8 stories above 10

Existing level 10-story

Application (c)
2010 Shanghai-Expo Theme Pavilion

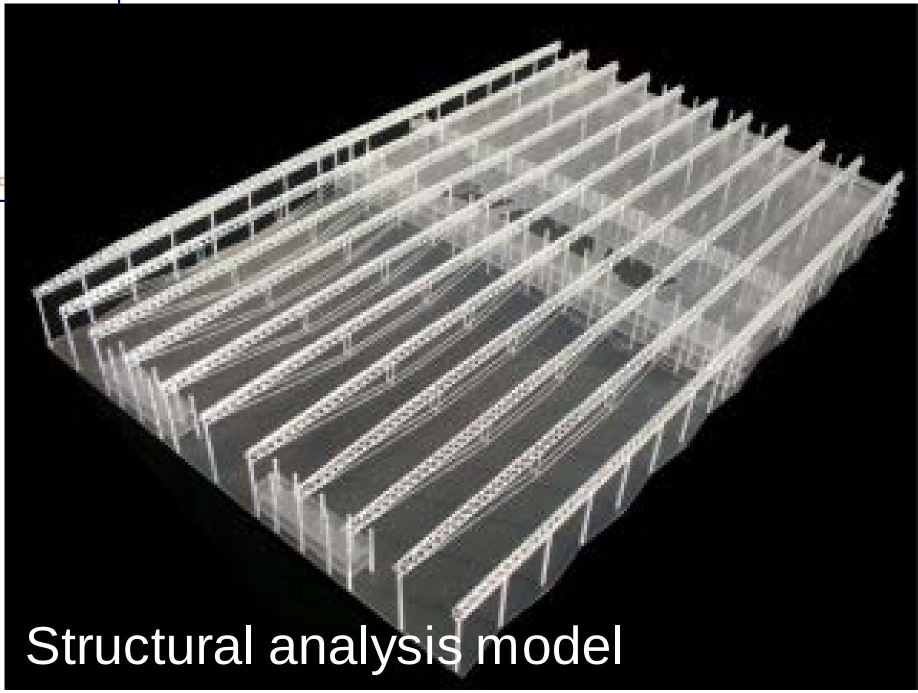


Description of the structure

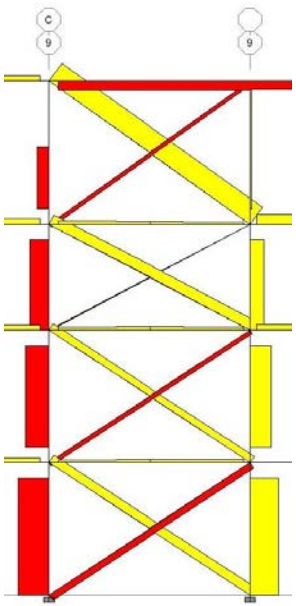


Structural elevation

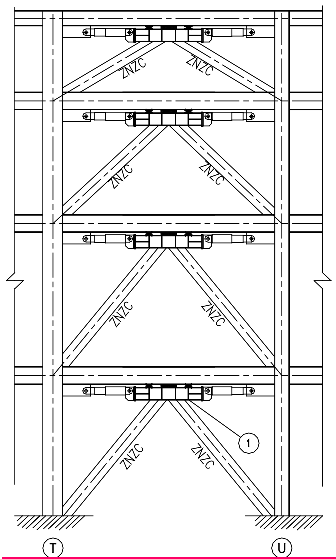
- The structure in Y direction is **unsymmetrical**.
- **Torsional response** is too large (T3/T1 and T3/T2) if moment steel frame is only used.

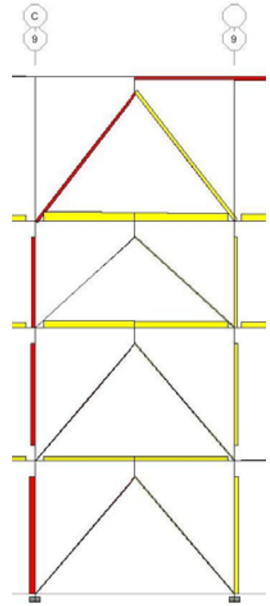

Structural analysis model

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



Rigid bracing



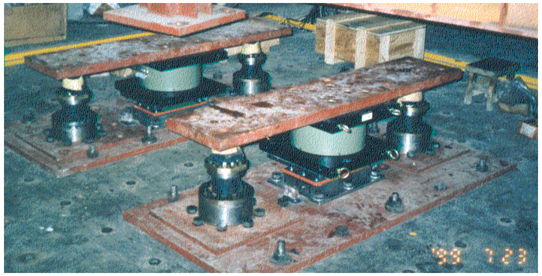


Damper bracing & internal forces

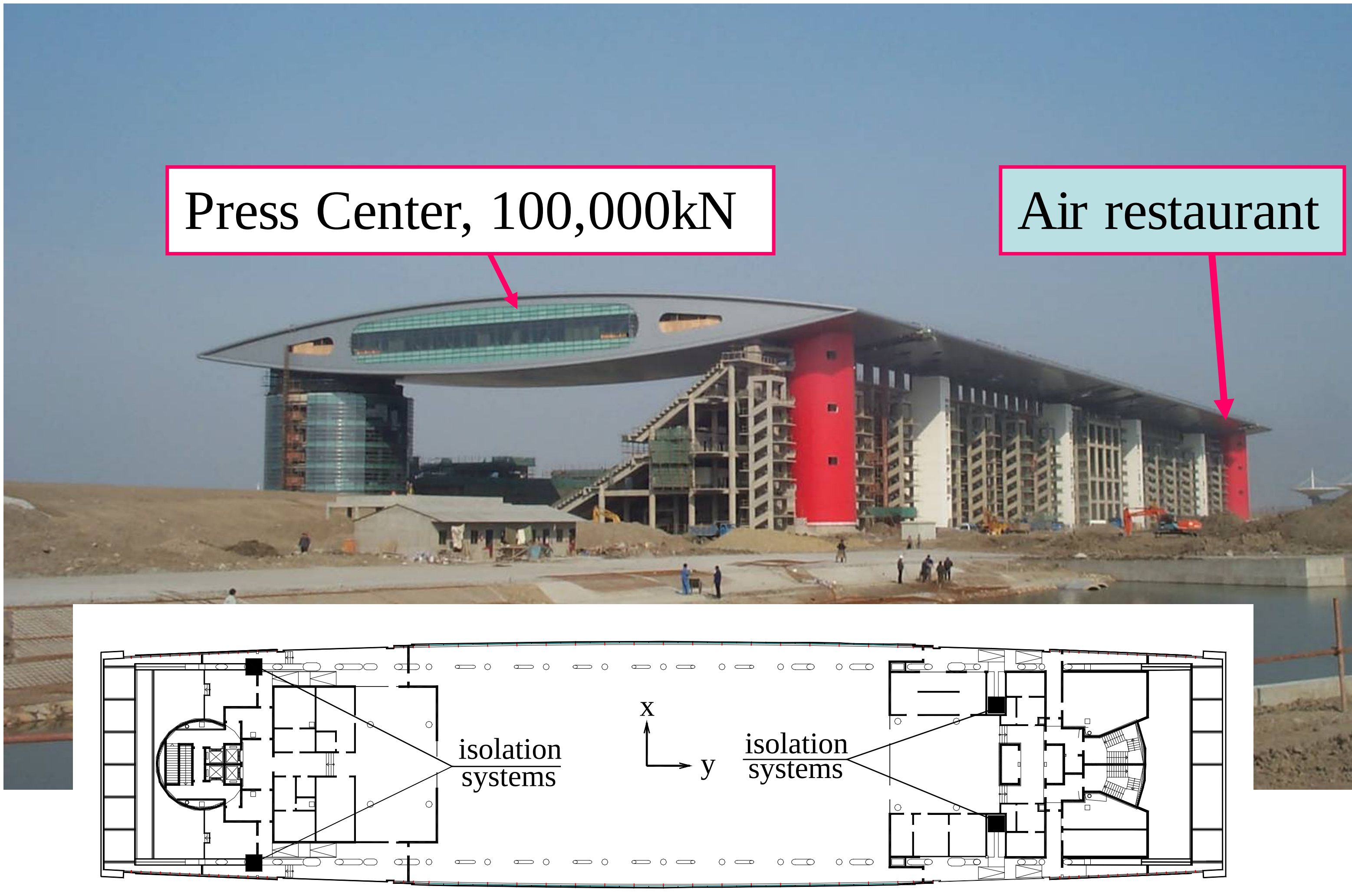
Combined energy dissipation bracing, oil damper and LRB, site photos of damper installation.

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.**



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



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

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 32 meters.

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

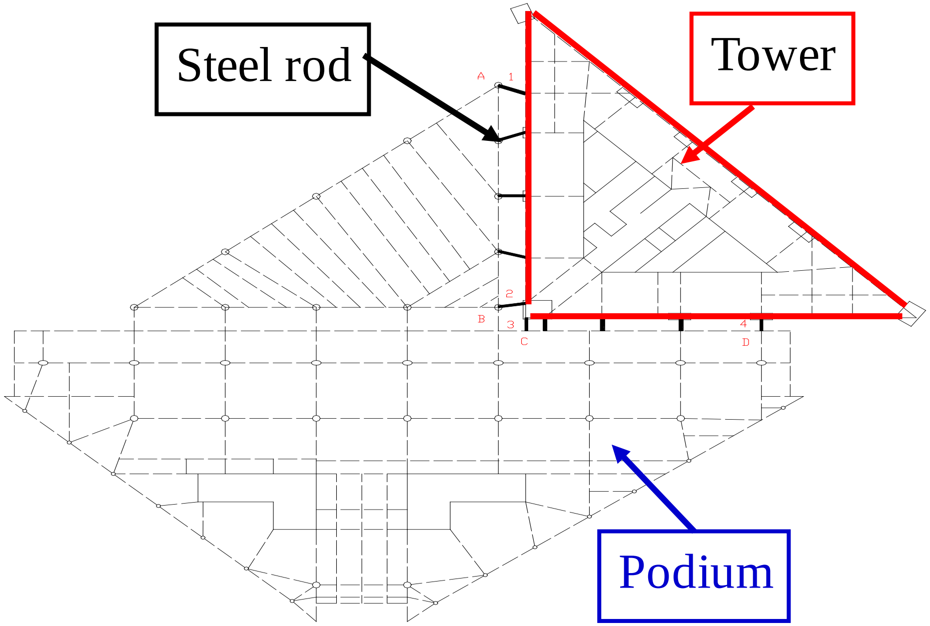
Overpass between buildings collapsed during Kobe earthquake of 1995

Adjacent structures linked by oil dampers in shaking table testing

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.



- During shaking table testing, the steel rods were broken in larger earthquake, and the design can not meet the requirements by Design Code.

- Therefore the oil dampers were selected to connect the main tower and podium structure instead of steel rods.

Design Parameters

Damper: 40 pieces;

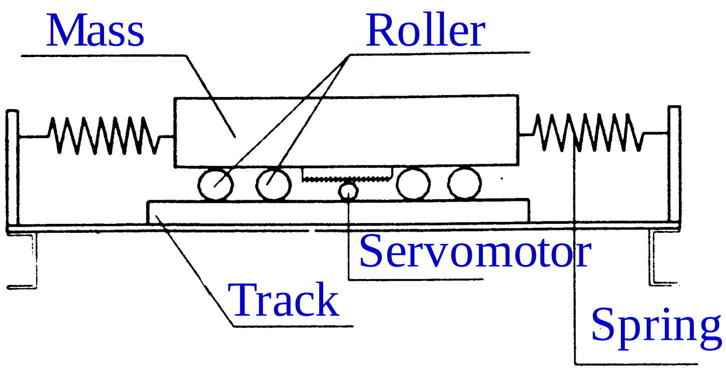
α= 0.15, C=250

Damping force: 500kN, 600kN

Locations of the dampers: floor levels on and below the roof of podium structures (7^{th} floor to 10^{th} floor).

Damper installation at the construction site

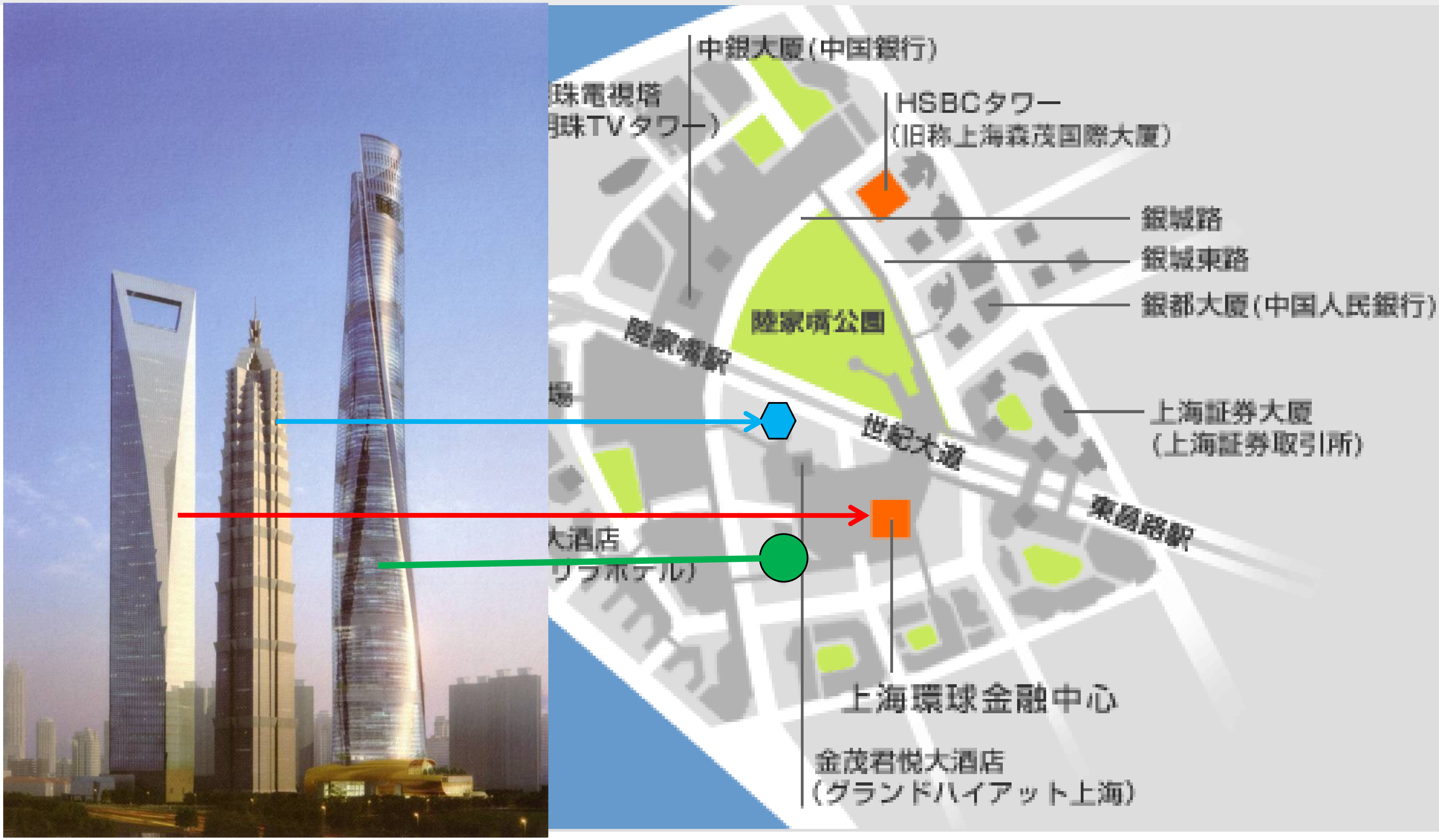
2.4 Vibration control study on tall buildings using TMD



- **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

(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)

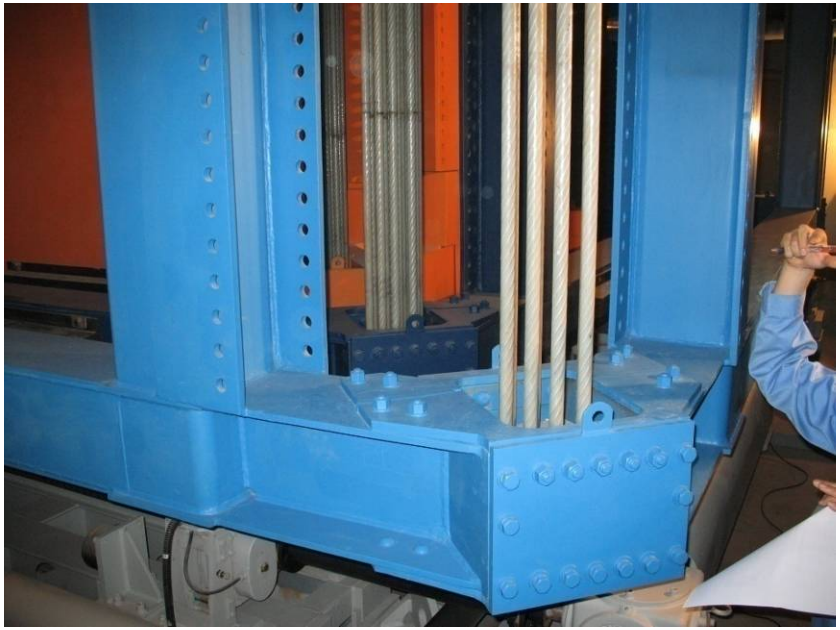
Damping ratio: 1% (wind), 4% (earthquake)

Moving mass: 150 t/set

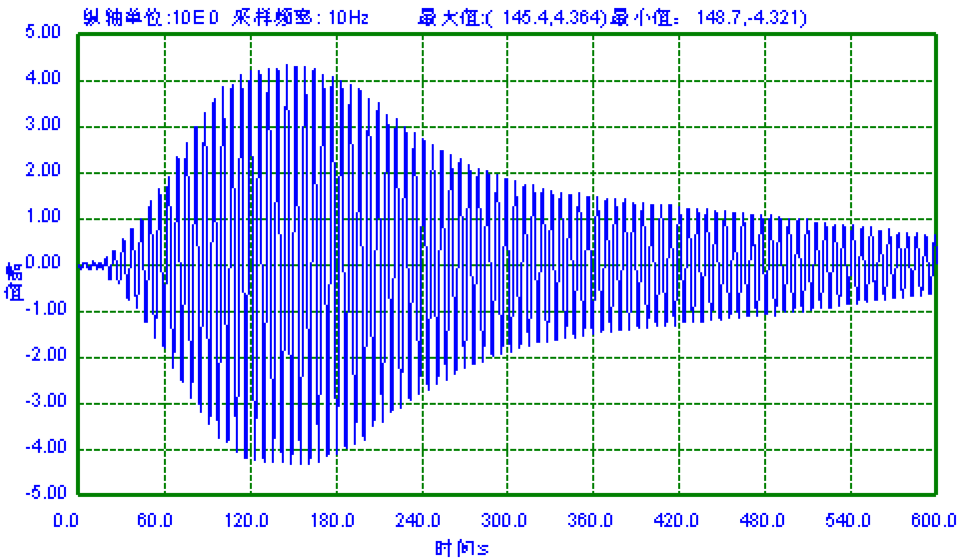
Amplitude of moving mass: ±1.1m

Completion date: May 30, 2008

Damper locations in 90th floor



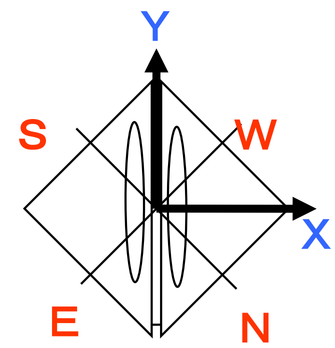
Device adjustment and inspection photos in construction site, May 1, 2008

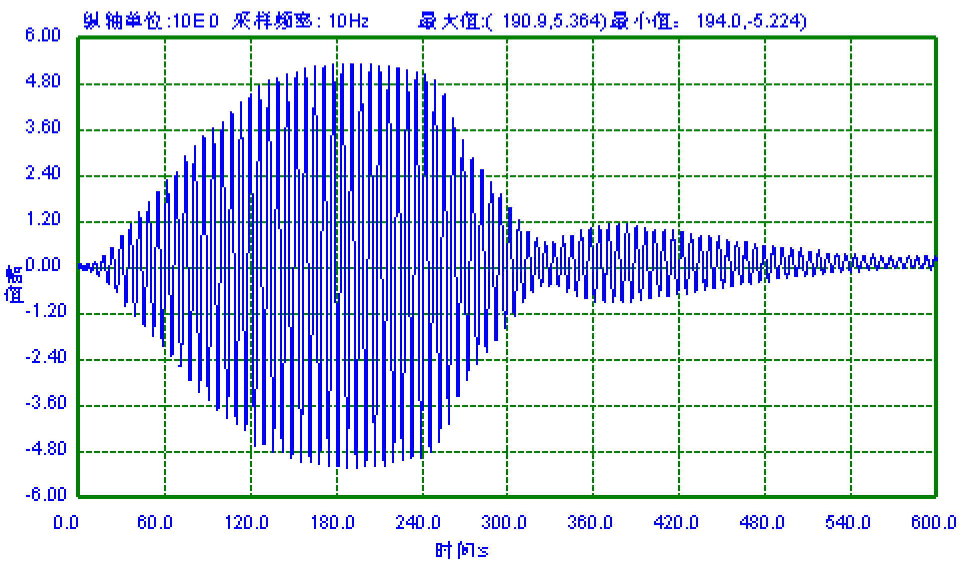


Structural response attenuation with TMD OFF

（damping ratio: 0.422%）

(Y direc.) Ty=6.502 sec.





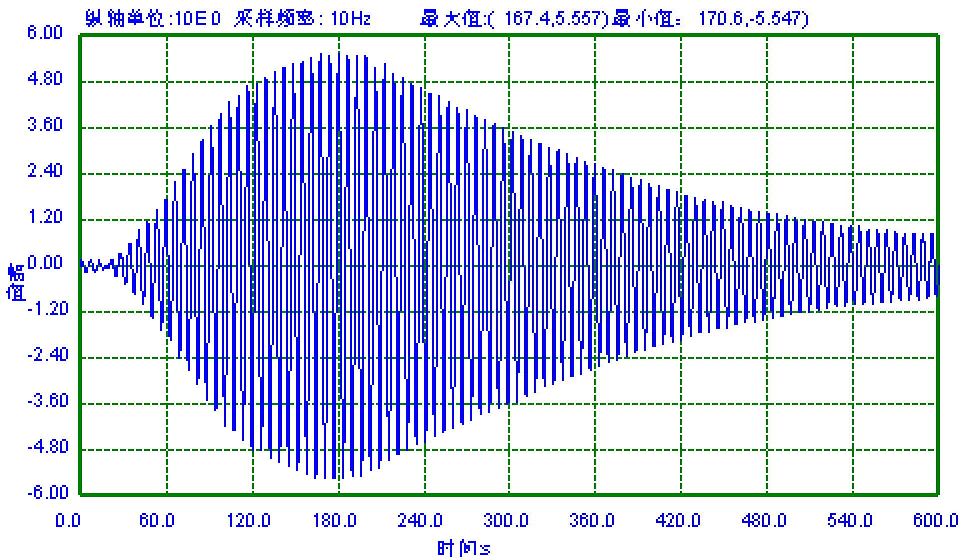
Structural response attenuation with TMD ON

（damping ration 3.404% ）

(Y direc.)

Ty=6.502 sec.

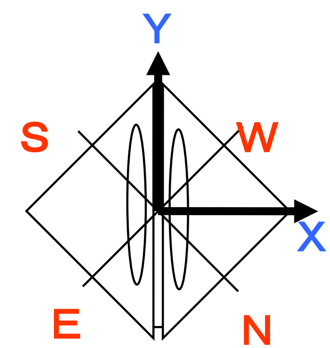
Calculated dynamic properties: 6.5166 sec.

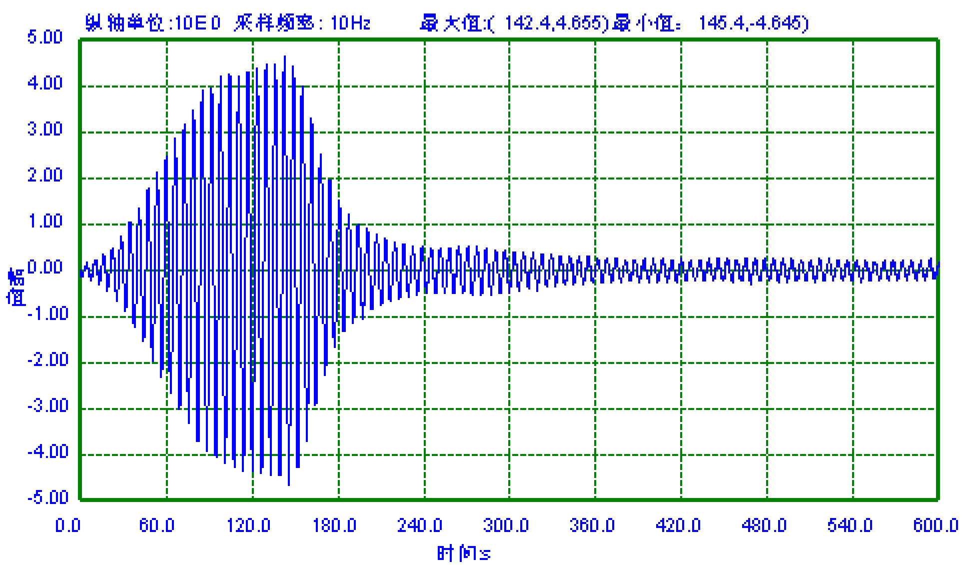


Structural response attenuation with TMD OFF

（damping ratio: 0. 459 %）

(X direc.) Tx=6.398 sec.





Structural response attenuation with TMD ON

（damping ratio: 3.865% ）

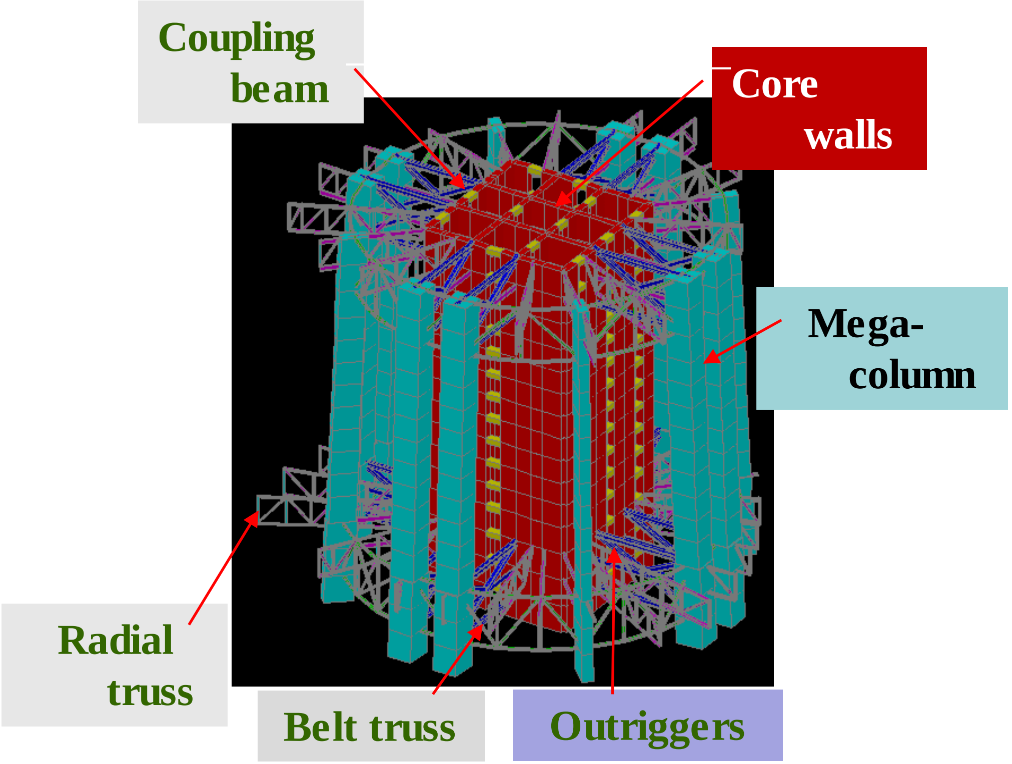
(X direc.) Tx=6.398 sec.

Calculated dynamic properties: 6.4469 sec.

（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

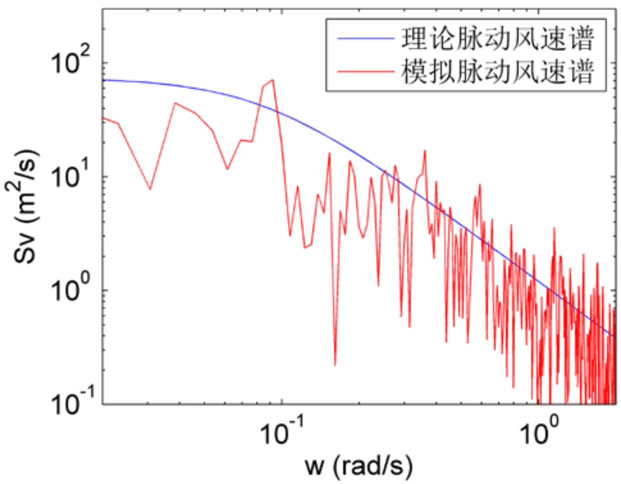


Model test on Wind Loading at Tongji（1/50 scale, 2010.7.20）

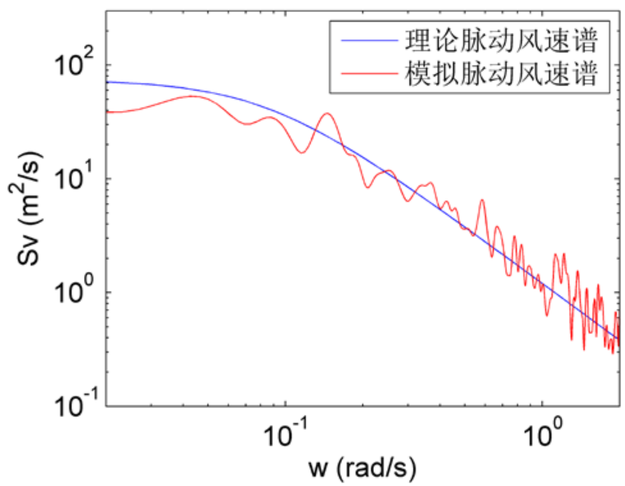
Model test on shaking table at Tongji（1/50 scale, 2010.7.30）

TMD design under wind loading for SH Tower

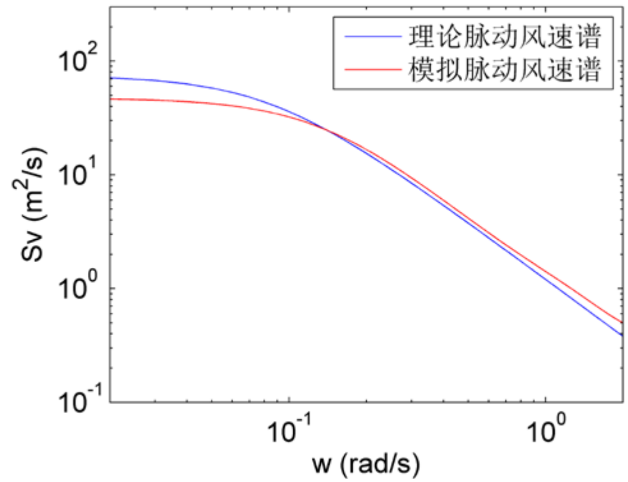
Wind spectrum by different creation methods



Bartlett method

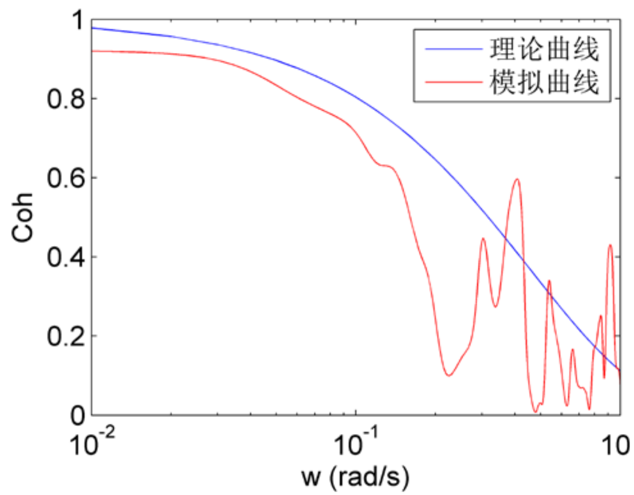


Welch method

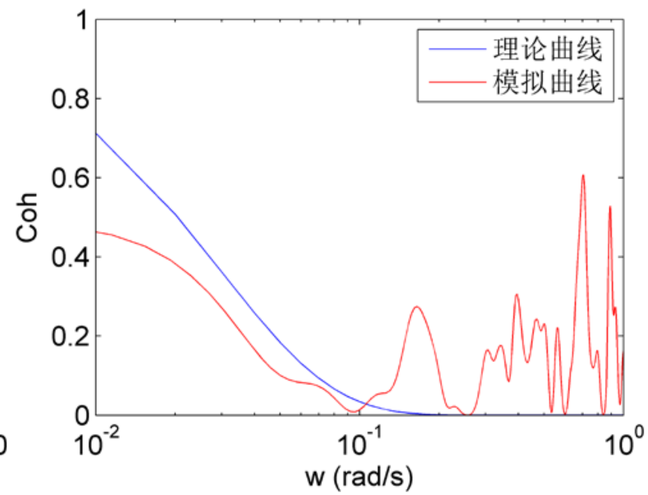


AR model

Wind spectrum coherence at different joints under one year return period



Joint 1 and joint 2



Joint 1 and joint 20

TMD parameter optimization

No control displacement

$$(\sigma_{x_k}^0)^2 = \varphi_{k1}^2 \int_{-\infty}^{+\infty} \left| H_{q_1}^0(i\omega) \right|^2 S_{f_1}(\omega) d\omega$$

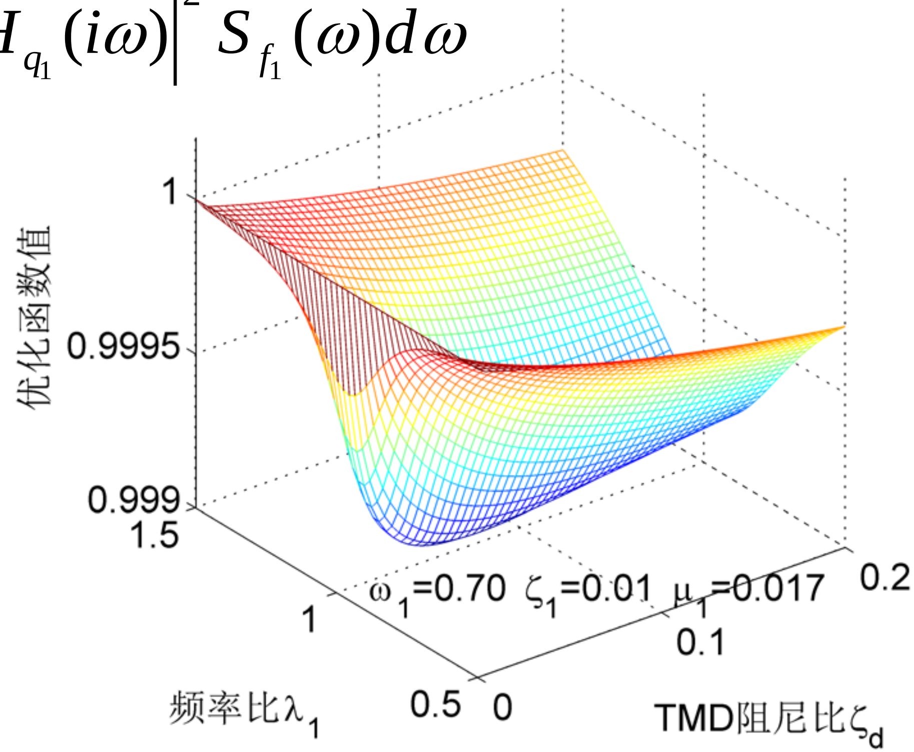
TMD control displacement

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

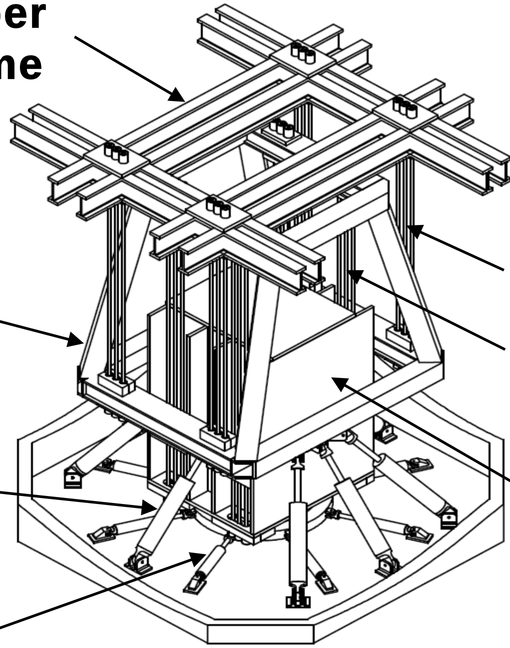
Vibration reduction factor

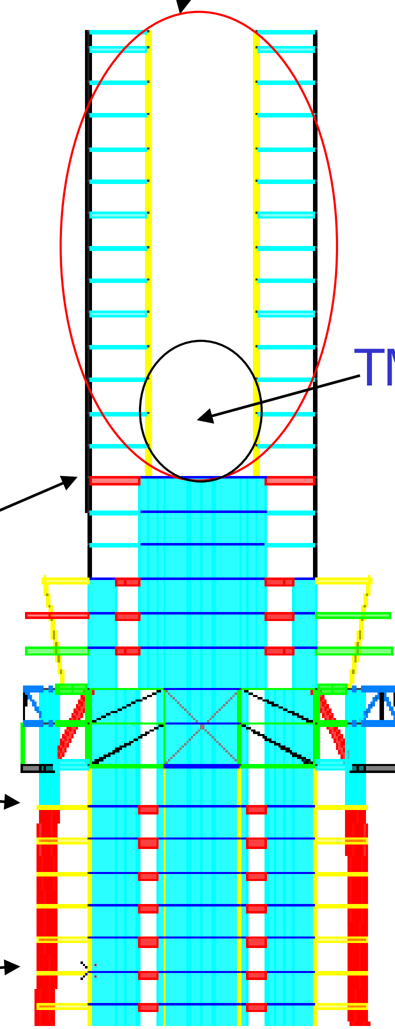
$$\delta_{x_k}^2 = \frac{(\sigma_{x_k})^2}{(\sigma_{x_k}^0)^2}$$

Through nonlinear optimization（MATLAB）



Optimization results

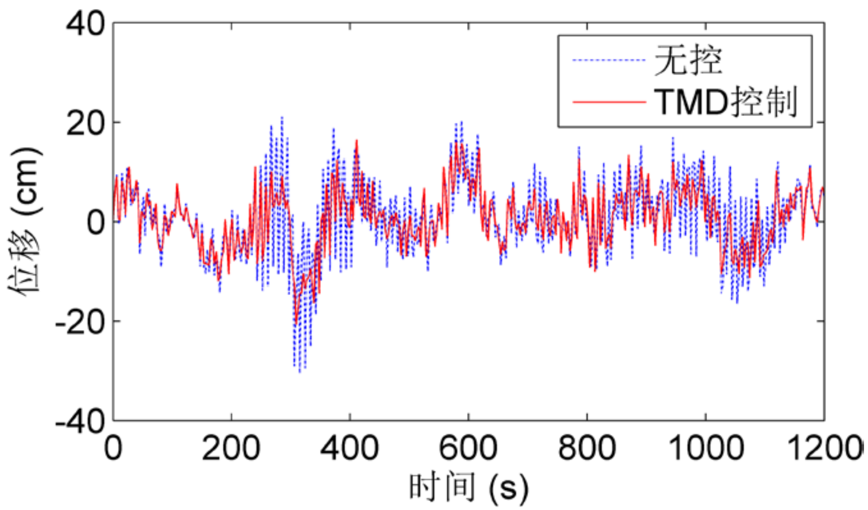


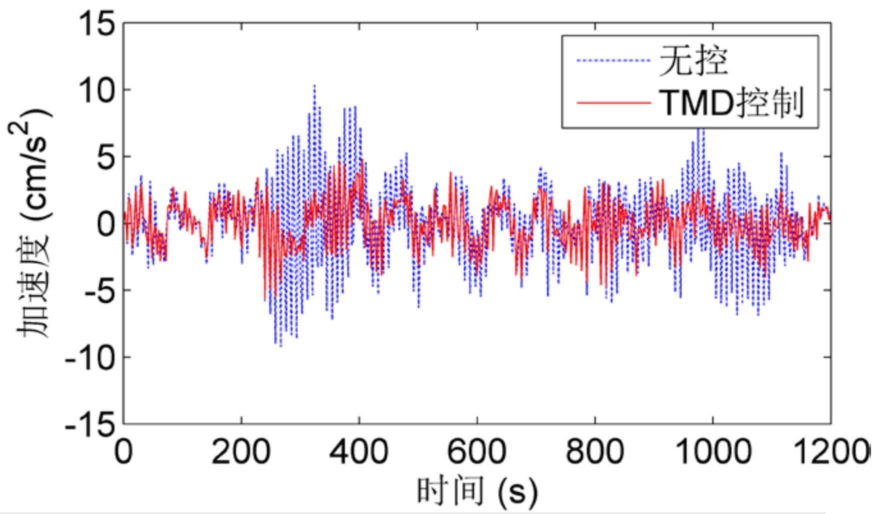


TMD structure demonstration (by RWDI)

Dynamic response under wind load

Wind speed RP	Floor	acceleration (cm/s^2)		TMD displacement (cm)	Damping force of oil dampers (kN)
		No TMD	With TMD		
1 year RP (wind speed: 25.8m/sec.)	115	6.5	2.7	35.3	9.10
	110	6.3	2.4		
10 years RP (wind speed: 36.3m/sec.)	115	11.4	6.2	81.9	21.2
	110	10.3	5.6		





Displacement & acceleration time history at No.115 floor under 10 year RP wind

3. FUTURE RESEARCH and Collaboration

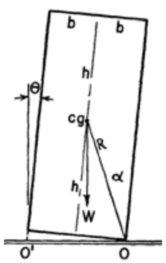
To create sustainable and damage-free tall buildings

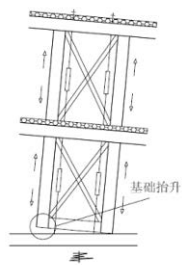
Earthquake Resilient Structures

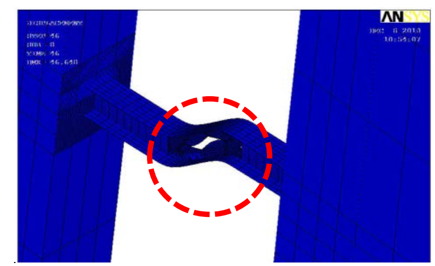
Rocking Structures

Self-centering Structures

Repairable structures with replaceable members







- Rocking RC shear walls
- Rocking frame-core walls with dampers

- Self-centering RC structures
- Self-centering timber structures with friction plates

Future Research Topics (1)

1). Development of new structural system that is sustainable, cost-effective, energy-saving and damage-free.

2). Smart material and smart structural system.

3). Implementation of performance-based seismic design of building structures, especially tall buildings.

Future Research Topics (2)

4). Development of new structural control devices with engineering application.

5). Development of new seismic testing methodologies.

5.1） Advanced laboratory testing techniques

5.2） Site test on prototype structures and its relations to design and analysis of structures

Thank you for your attention!

Any question?

Or Comments?