



3rd International Conference on Advances in Experimental Structural Engineering  
October 15-16, 2009, San Francisco




# SHAKING TABLE MODEL TEST OF A SUPER HIGH-RISE BUILDING WITH SETBACKS IN ELEVATION

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# CONTENTS:

- **DESCRIPTION OF THE BUILDING**
- **MODEL DESIGN AND CONSTRUCTION**
- **TEST PROGRAM**
- **TEST RESULTS**
- **DYNAMIC RESPONSE OF THE PROTOTYPE  
STRUCTURE**
- **CONCLUSIONS AND SUGGESTIONS**

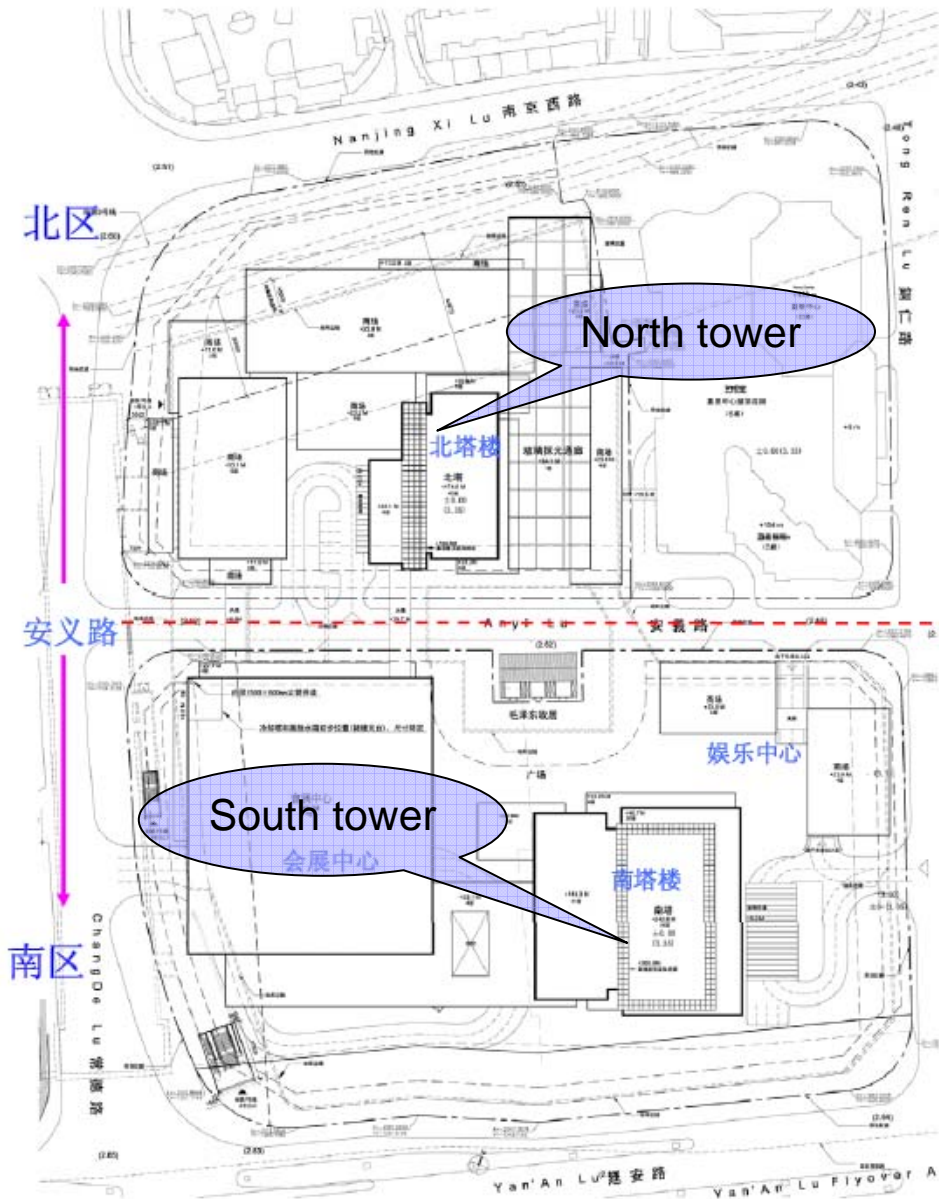


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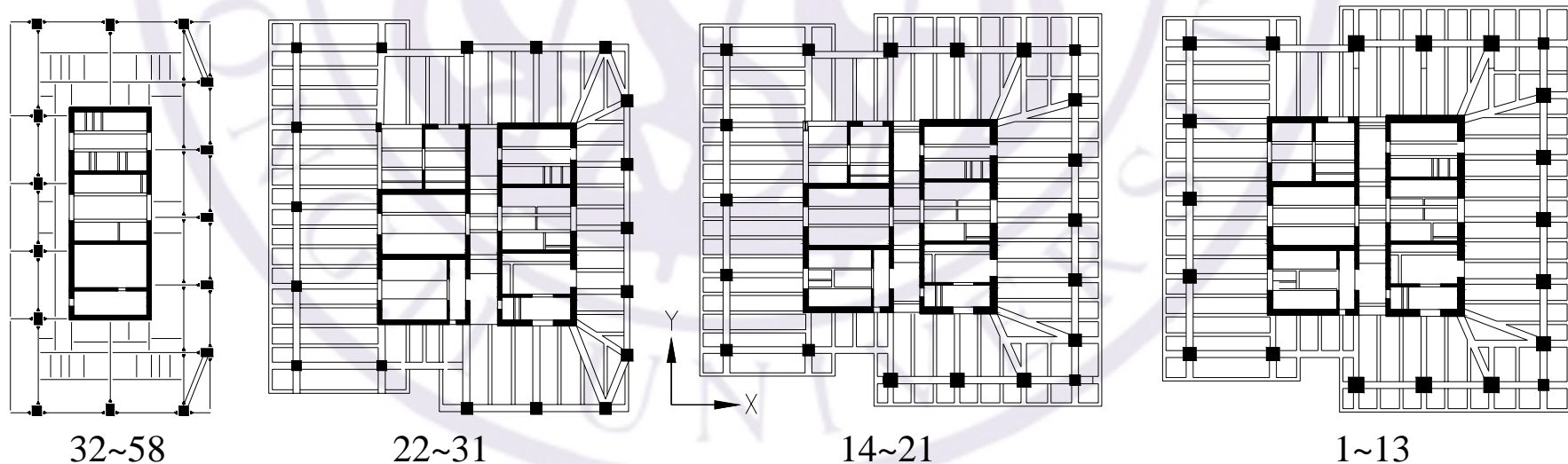
# DESCRIPTION OF THE BUILDING

# Where the building is and what does it look like?



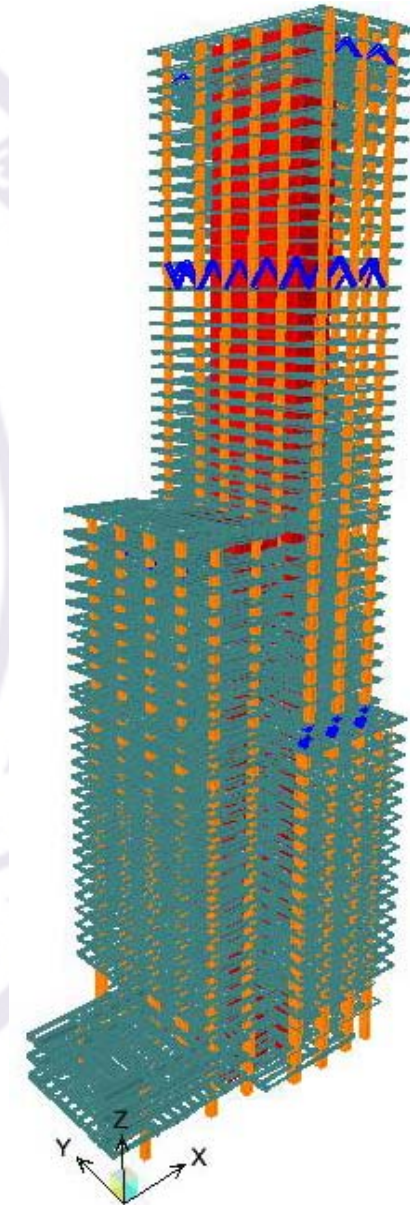
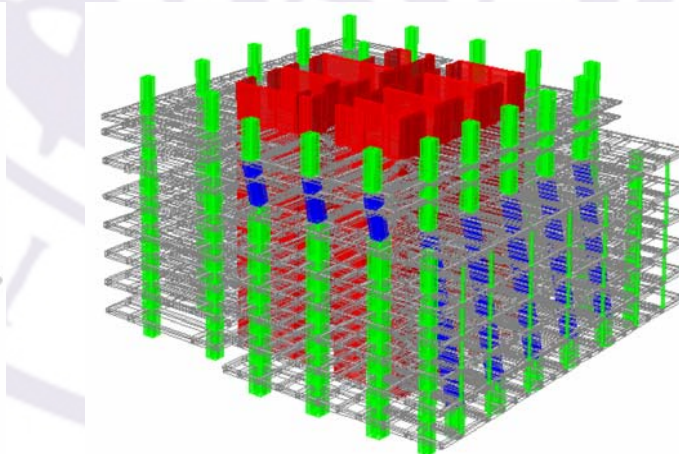
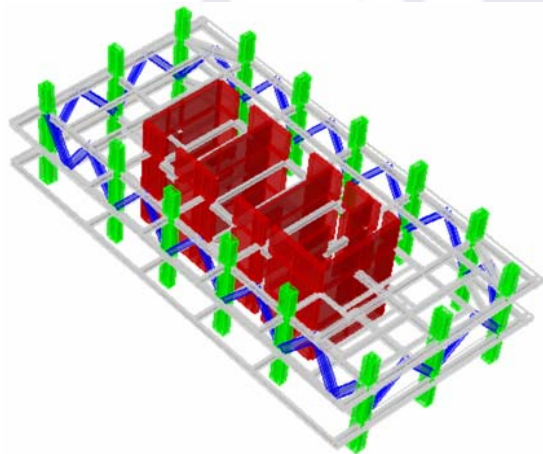
# Facts about the building

- Function——office building; hotel
- Storey——58 stories over the ground  
4 stories underneath the ground
- Height——244.8m(the top of the roof)  
260.0m(the top of the steel frame)
- Typical plans——



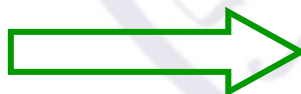
# Structure system and characteristics

- SRC frame
- RC core
- Belt truss storey
- Setbacks in the 21st and 31st floor
- Two sets of inclined columns
  - five columns, 16~21,  $11.5^\circ$
  - three columns, 21~22,  $13.2^\circ$



# Why a shaking table model test is needed?

- According to the **Chinese Code for Seismic Design of Building** (CCSDB, GB 50011-2001) and **Technical Specification for Concrete Structures of Tall Building** (TSCSTB, JGJ3-2002), the height of the building exceeds the stipulated maximum height of 190m for a SRC frame and RC core system.
- The height of the setback is 101.9m, which is about 41.7% of the overall structural height. The two setbacks in elevation make it difficult to keep the vertical elements successive.

 out-of-code; irregularity; complexity



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# MODEL DESIGN AND CONSTRUCTION

# Shaking table facility

Item		Performance
Maximum Payload		25tons
Table Size		4m×4m
Excitation Control		X, Y and Z Simultaneously with 6 DOF
Maximum Stroke		X: ±100mm, Y and Z: ±50mm
Maximum Velocity		X: 1000mm/s, Y and Z: 600 mm/s
Maximum Acceleration	X	4.0g (bare table), 1.2g~0.8g (15~25tons)
	Y	2.0g (bare table), 0.8g~0.6g (15~25tons)
	Z	4.0g (bare table), 0.7g~0.5g (15~25tons)
Frequency Range		0.1~50Hz
DAS Channel		96/STEX3

# Material selection and test

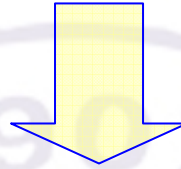
- Concrete——fine aggregate concrete;
- Reinforcement——galvanized iron wires;
- Steel——red copper;



# Similitude relationship

- Dynamic similitude equilibrium equation  $S_E / S_\rho S_a S_l = 1$
- Based on the capacity, the size of the shaking table and the height of the laboratory,  **$S_l$  was chosen as 1/35**. Therefore the model was built with a total height of 7.429m.
- Empirically,  $S_E$  was firstly considered between 1/5~1/3 and then determined to be **0.30** according to the material test results.
- Considering the capacity of the shaking table and to avoid the disturbance of the noise,  **$S_a$  was set to be 3.0**.

## similitude theory



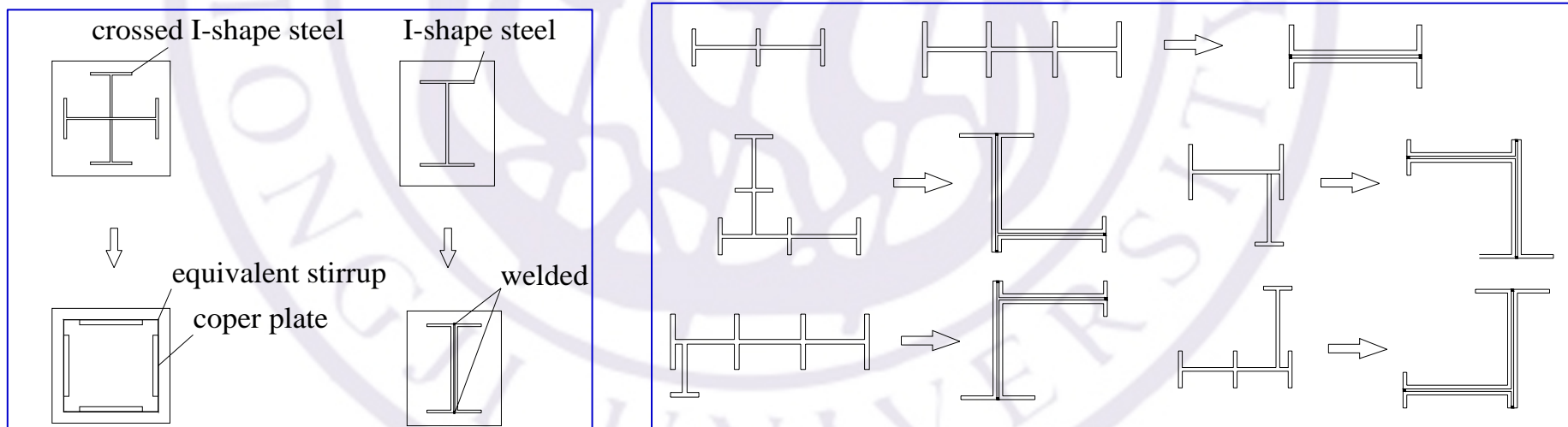
Parameters	Relationships	Model/prototype
Length	$S_l$	1/35
Elastic modulus	$S_E$	0.30
Stress	$S_\sigma$	0.30
Strain	$S_\sigma/S_E$	1.00
Density	$S_\rho$	3.50
Force	$S_F$	2.45E-04
Frequency	$S_f$	10.25
Acceleration	$S_a$	3.00



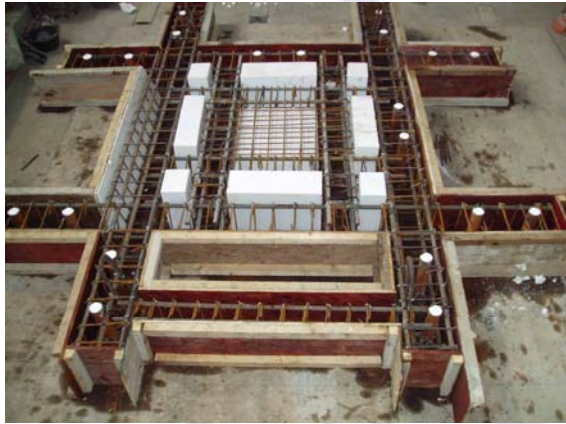
# Member design and simplification

- **RC members:**
  - bending capacity equivalent of normal section
  - shearing capacity equivalent of diagonal section
- **Steel in SRC members:** equivalent of stiffness
- **Truss members:** equivalent of axial force
- **Openings:** normalized
- **Secondary beams:** excluded and compensated by modifying the slab
- **Complex steel sections:**

- **Crossed I-shape steel**  $\Rightarrow$  four copper plates  
additional stirrup
- **I-shape steel**  $\Rightarrow$  two C-shape copper plates
- **Complex steel**  $\Rightarrow$  an I-shape and a T-shape copper plate



# Process of model construction



Base of the Model



Typical Floor



Inclined Columns



Belt Truss Storey



Model Panorama



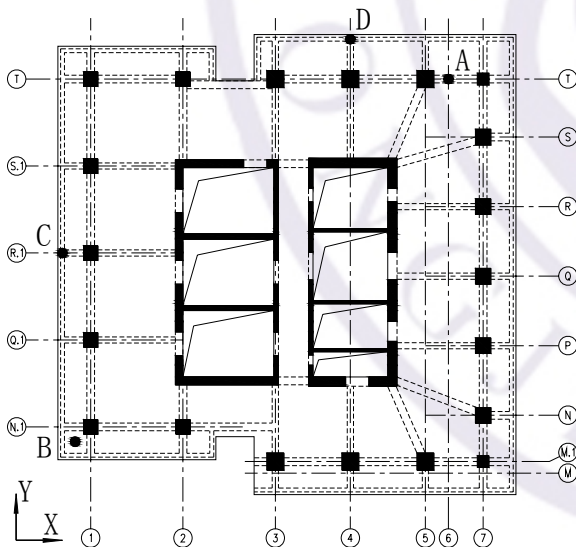
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# TEST PROGRAM

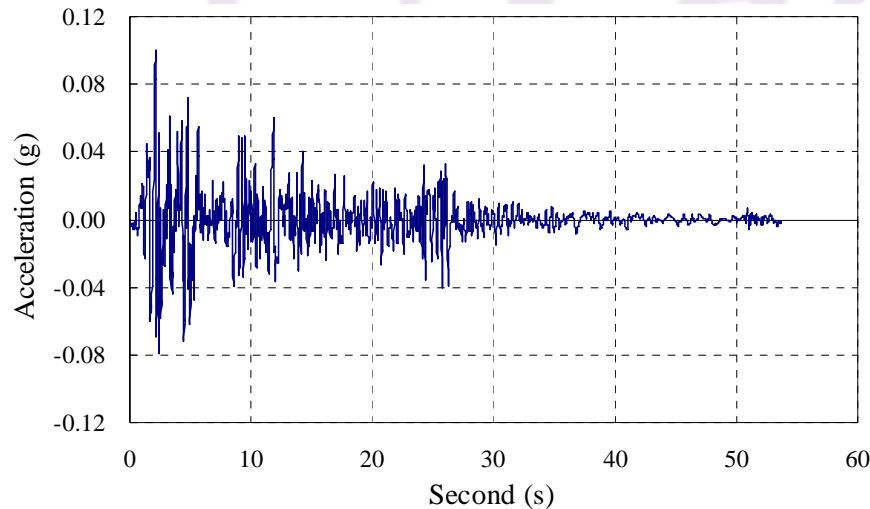
# Instruments and transducers

- **35 accelerometers** were installed on the key stories along the height of the model, they were the roof, the 47<sup>th</sup>, the 38<sup>th</sup>, the 31<sup>st</sup>, the 21<sup>st</sup>, the 16<sup>th</sup>, the 10<sup>th</sup>, the 5<sup>th</sup> floor, and the base in two or three directions.
- **12 displacement transducers** were installed at the roof, the 47<sup>th</sup>, the 31<sup>st</sup>, the 21<sup>st</sup> floor and the base.

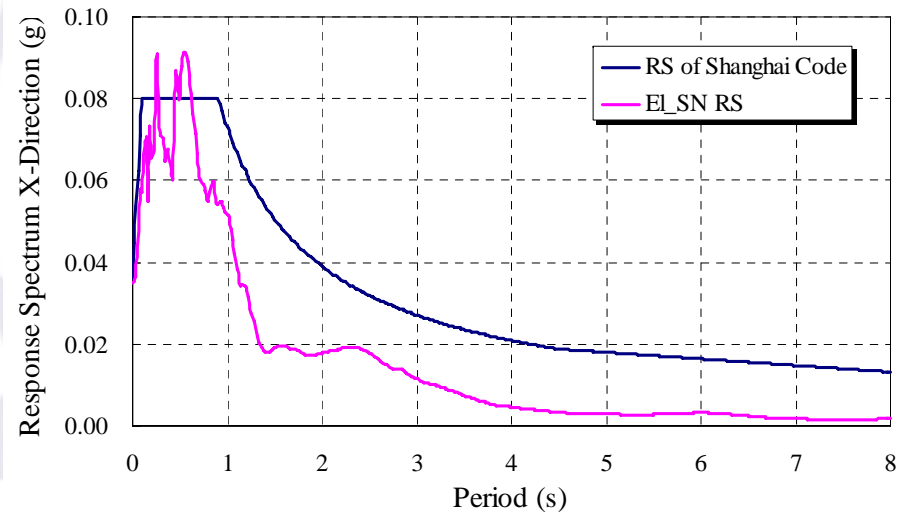


# Ground motion input

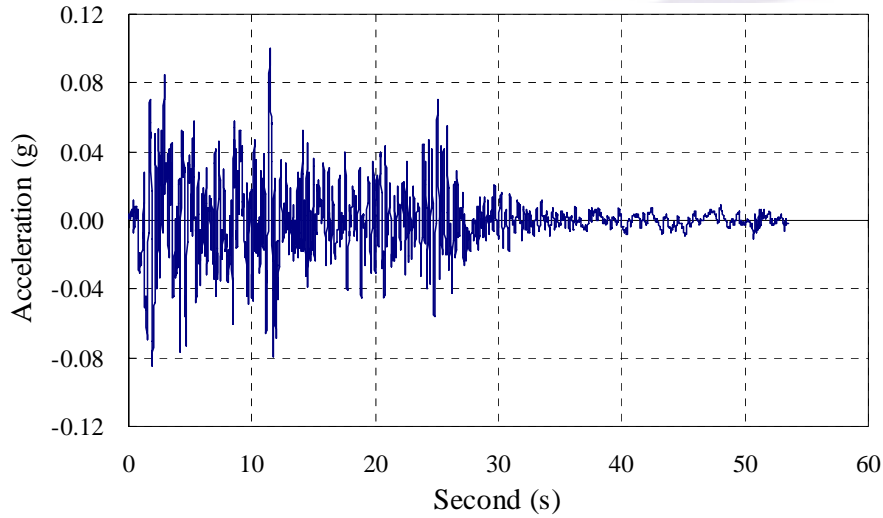
- EL Centro
- Pasadena
- Shanghai artificial wave SHW1



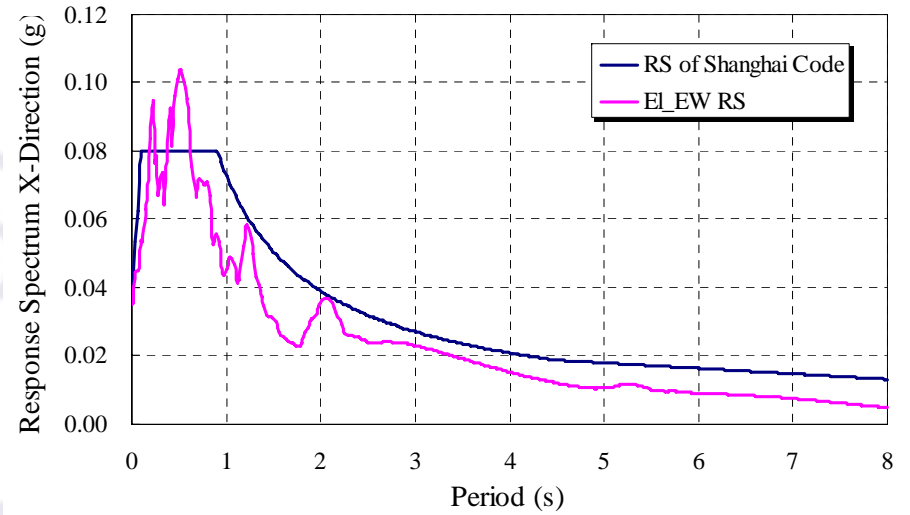
Time history of EL Centro ground motion record  
in south-north direction



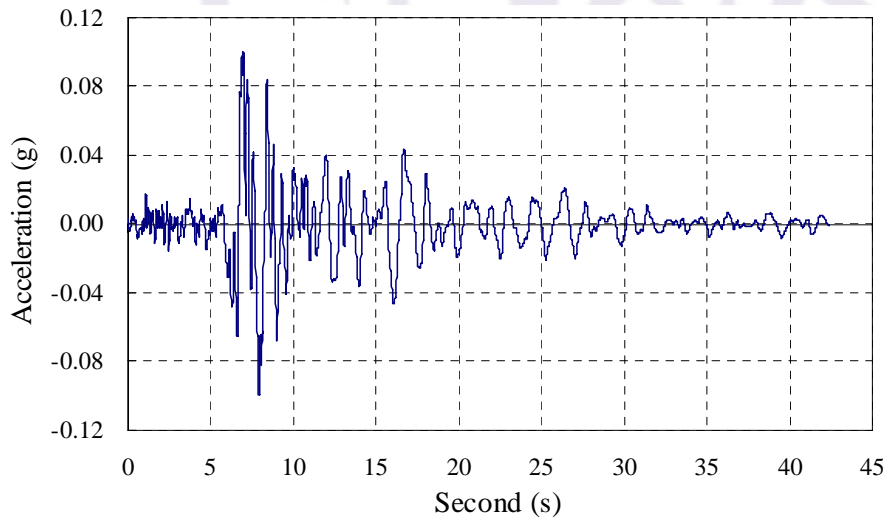
Response spectrum of EL Centro SN and that of  
Shanghai Code for Seismic Design of Buildings



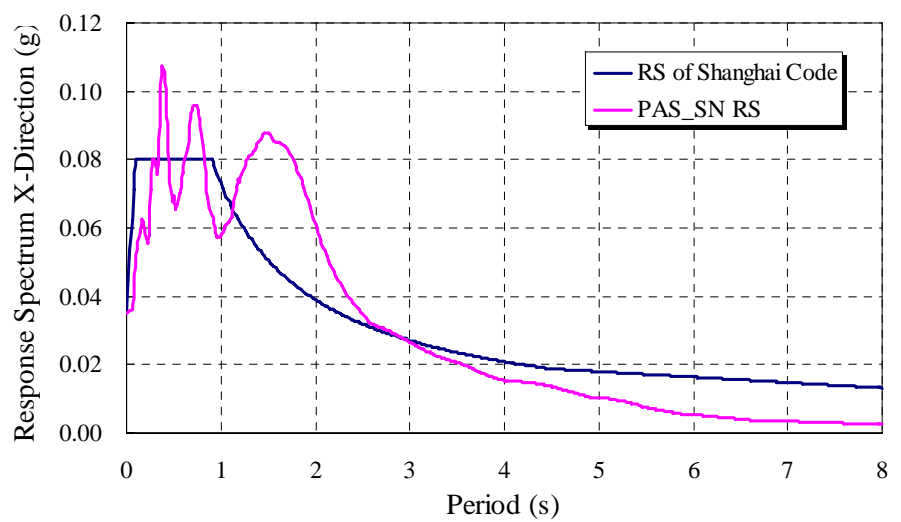
Time history of EL Centro ground motion record in east-west direction



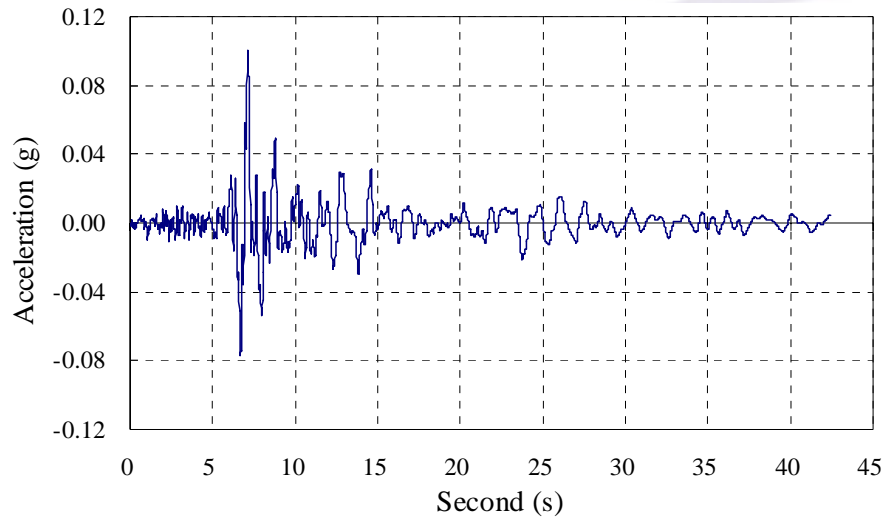
Response spectrum of EL Centro EW and that of Shanghai Code for Seismic Design of Buildings



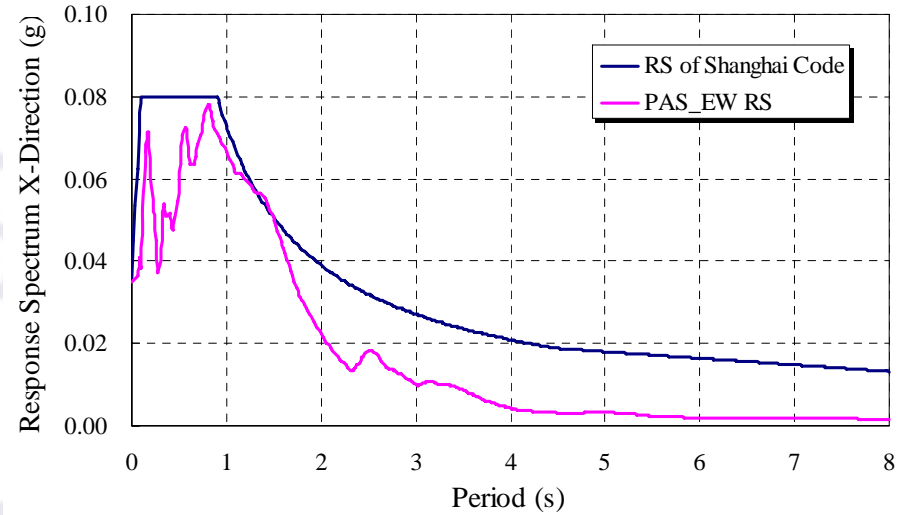
Time history of Pasadena ground motion record in south-north direction



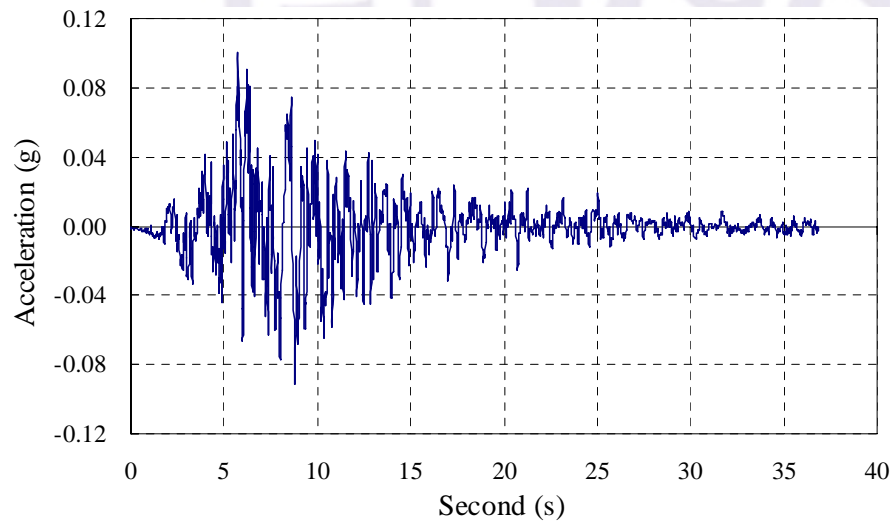
Response spectrum of Pasadena SN and that of Shanghai Code for Seismic Design of Buildings



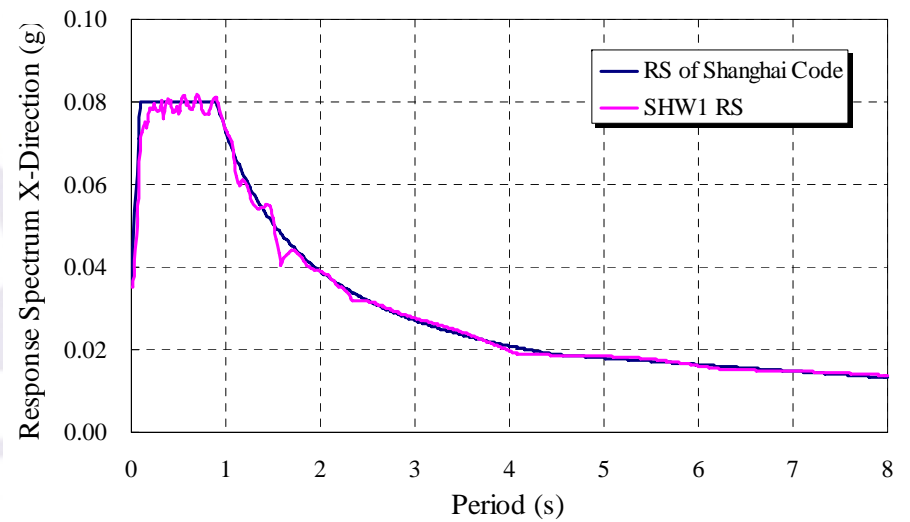
Time history of Pasadena ground motion record in east-west direction



Response spectrum of Pasadena EW and that of Shanghai Code for Seismic Design of Buildings



Time history of Shanghai artificial wave SHW1



Response spectrum of SHW1 and that of Shanghai Code for Seismic Design of Buildings

# Test program

- **Seismic design intensity: 7**
- **Design basic acceleration of ground motion: 0.1g**
- **Four phases:**
  - The frequent occurrence of seismic design intensity 7, 0.035g
  - The moderate occurrence of seismic design intensity 7, 0.1g
  - The rare occurrence of seismic design intensity 7, 0.2g
  - The rare occurrence of seismic design intensity 8, 0.36g
- **Peak value of input acceleration:**
  - The design acceleration times  $S_a$ .
- **White noise test**
- **Input directions:**
  - SHW1: 1-D
  - EL Centro and Pasadena: 2-D (first three phases); 3-D (the forth phase)
  - White noise cases: 3-D

## Test Program

Test case	Case name	Earthquake Occurrence Frequency	Input Signal	Peak value of input acceleration (g)						Note
				Direction X		Direction Y		Direction Z		
				Design	Achieved	Design	Achieved	Design	Achieved	
1	W1	White noise 1		0.05		0.05		0.05		3D
2	F7EXY	Frequent 7	El Centro	0.11	0.128	0.09	0.097			2D
3	F7EYX			0.09	0.101	0.11	0.152			
4	F7PXY		Pasadena	0.11	0.129	0.09	0.073			2D
5	F7PYX			0.09	0.126	0.11	0.163			
6	F7SHX		SHW1	0.11	0.123					1D
7	F7SHY					0.11	0.155			
8	W2		White noise 2		0.05		0.05		0.05	
9	B7EXY	Moderate 7	El Centro	0.30	0.342	0.26	0.276			2D
10	B7EYX			0.26	0.261	0.30	0.264			
11	B7PXY		Pasadena	0.30	0.349	0.26	0.281			2D
12	B7PYX			0.26	0.299	0.30	0.348			
13	B7SHX		SHW1	0.30	0.436					1D
14	B7SHY					0.30	0.304			

Test case	Case name	Earthquake Occurrence Frequency	Input Signal	Peak value of input acceleration (g)						Note
				Direction X		Direction Y		Direction Z		
				Design	Achieved	Design	Achieved	Design	Achieved	
15	W3	White noise 3		0.05		0.05		0.05		3D
16	R7EXY	Rare 7	El Centro	0.60	0.713	0.51	0.418			2D
17	R7EYX			0.51	0.526	0.60	0.508			
18	R7PXY		Pasadena	0.60	0.741	0.51	0.573			2D
19	R7PYX			0.51	0.552	0.60	0.593			
20	R7SHX		SHW1	0.60	0.803					1D
21	R7SHY					0.60	0.471			
22	W4	White noise 4		0.05		0.05		0.05		3D
23	R8EXY	Rare 8	El Centro	1.08	1.407	0.92	0.803	0.70	0.716	3D
24	R8EYX			0.92	1.227	1.08	1.33	0.70	0.654	
25	R8PXY		Pasadena	1.08	1.716	0.92	1.119	0.70	1.012	
26	W5	White noise 5		0.05		0.05		0.05		3D

# Pictures





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# TEST RESULTS



# Cracking and failure pattern

- White noise 1
- Frequent 7
- White noise 2
- Moderate 7
- White noise 3: frequency decreased slightly in two direction
- Rare 7: several cracks were observed
- White noise 4: frequency decreased continuously

# Cracking and failure pattern

- Rare 8:

Existing cracks further propagated;

Crossing cracks appeared in the columns of stories above and under the setbacks and concrete crushed locally, especially in the setback storey;

Diagonal cracks run through the whole shear walls in the setback storey;

Columns above the inclined columns of the 22nd floor cracked horizontally and vertically;

No damage was observed in the bottom shear walls and the truss members in the belt truss storey.



shear wall diagonal crack  
in the 30th storey



column diagonal crack  
in the 31st storey



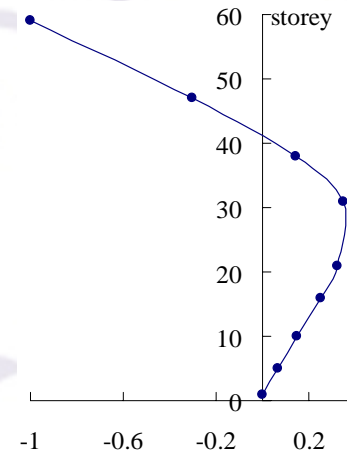
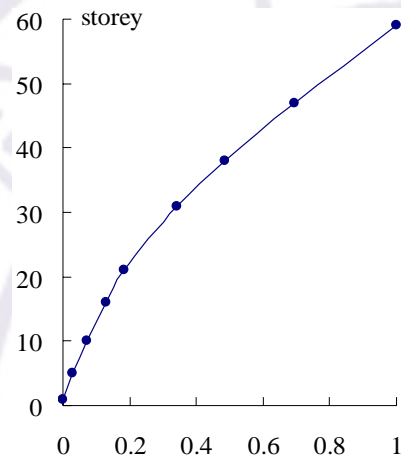
column crossing crack  
in the 32nd storey

# Dynamic property of the model structure

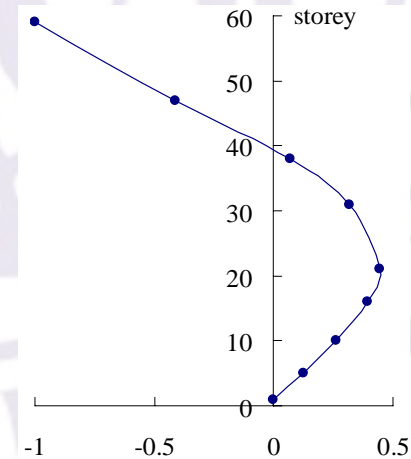
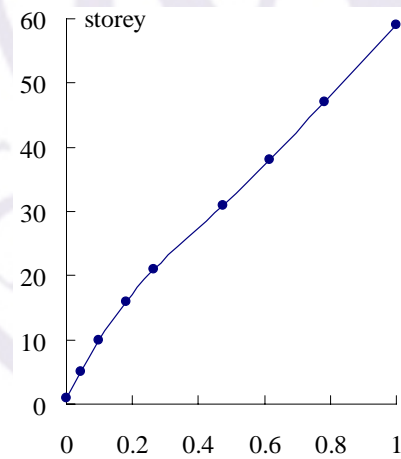
The first three frequencies and modal shapes of model structure

No.		1	2	3
White noise 1	Frequency	3.418Hz	3.418Hz	6.347Hz
	Modal shape	X	Y	T
White noise 2	Frequency	3.418Hz	3.418Hz	6.347Hz
	Modal shape	X	Y	T
White noise 3	Frequency	2.930Hz	2.930Hz	—
	Modal shape	X	Y	T
White noise 4	Frequency	2.930Hz	2.930Hz	5.371Hz
	Modal shape	X	Y	T
White noise 5	Frequency	2.441Hz	2.441Hz	—
	Modal shape	X	Y	T

# Dynamic property of the model structure

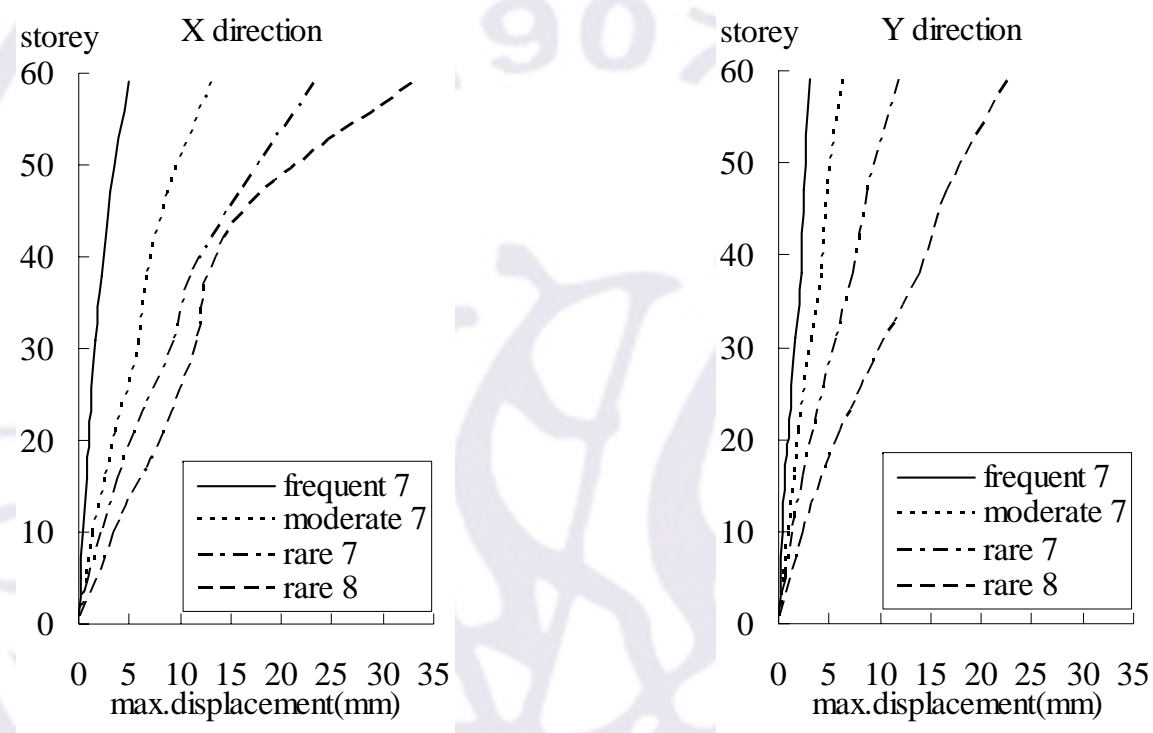


the first two modal shape in the X direction



the first two modal shape in the Y direction

# Displacement response of model structure



Displacement response envelopes of the model structure



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# **DYNAMIC RESPONSE OF THE PROTOTYPE STRUCTURE**

# Dynamic property of prototype structure

The first three frequencies and modal shapes of prototype structure

No.		1	2	3
White noise 1	Frequency	0.333Hz	0.333Hz	0.619Hz
	Modal shape	X	Y	T
White noise 2	Frequency	0.333Hz	0.333Hz	0.619Hz
	Modal shape	X	Y	T
White noise 3	Frequency	0.286Hz	0.286Hz	—
	Modal shape	X	Y	T
White noise 4	Frequency	0.286Hz	0.286Hz	0.524Hz
	Modal shape	X	Y	T
White noise 5	Frequency	0.238Hz	0.238Hz	—
	Modal shape	X	Y	T

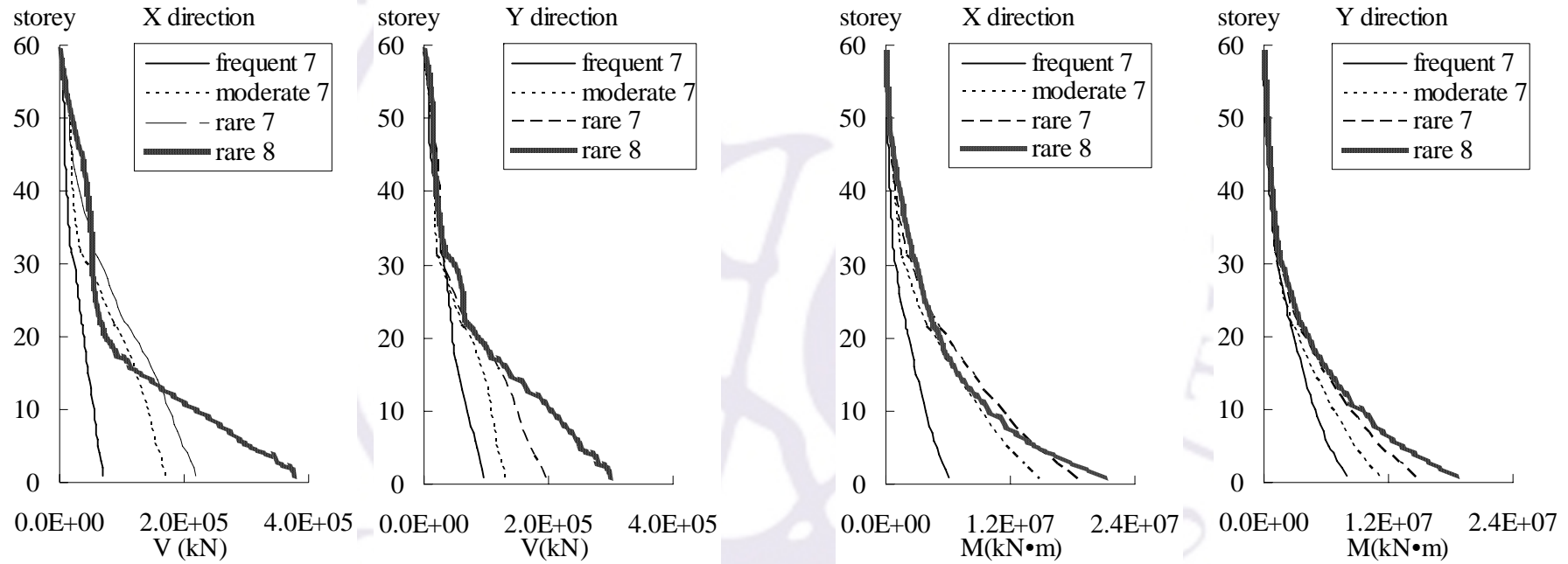
- The frequency ratio between the first translational mode to the first torsional mode is 0.538, which is less than the stipulated value 0.85 in the TSCSTB.

# Displacement Response and Inter-Storey Drift Angle of Prototype Structure

The maximum inter-storey drift angle of prototype structure

Test phase	Frequent 7		Moderate 7		Rare 7		Rare 8	
	X	Y	X	Y	X	Y	X	Y
Max. inter-storey drift angle	1/838	1/1611	1/352	1/801	1/207	1/308	1/138	1/218
Coded value	1/500	1/500			1/100	1/100		

# Storey Shear Force Distribution and Overrunning Moment of Prototype Structure



Envelops of shear force

Envelops of overturning moment



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# CONCLUSIONS AND SUGESSTIONS



## Conclusions

- Under frequent occurrence of seismic design intensity 7, no visible damage can be observed. The natural frequency remained unchanged. Under moderate occurrence of seismic design intensity 7, the natural frequency decreased very slightly, which indicates that the prototype structure can behave elastically when attacked by those levels of earthquakes. Under rare occurrence of seismic design intensity 7 and 8, the structure damaged locally but still could survive and keep stable, which indicates that the target high-rise building **could meet the design criteria of no damage under frequent earthquake and no collapse under rare earthquake;**



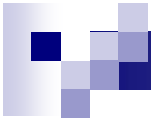
## Conclusions

- The maximum inter-storey drift angles are  $1/838$  and  $1/1611$  in X and Y direction under frequent earthquake 7 phase, which are less than the limitation of  $1/500$  by the TSCSTB. In the rare occurrence of seismic design intensity 7 phase, the maximum inter-storey drift angles are  $1/207$  and  $1/308$  in X and Y direction, which satisfy the limitation of  $1/100$  by the TSCSTB.



# Suggestions

- When a very rare earthquake attacks, the setback storey damaged severely due to the sudden change in stiffness, which may leads to the weak point of the structure. It is suggested that appropriate improvement on ductility should be made to the stories adjacent to setbacks;
- The angle between the inclined columns in the 21st to the 22nd storey and the vertical direction should be decreased to improve the seismic performance of the structure.



The end!  
Thanks for your attention!

