Dynamic Test on a Multi-tower Connected Building Structure

Ying ZHOU; Xilin LU;
Wensheng LU; Jiang QIAN

State Key Laboratory for Disaster Reduction in Civil Engineering,
Tongji University, Shanghai 200092, China
Background

- China has been building up a large number of novel high-rise buildings, under an increasing requirement of architectural aesthetics.
Background

- 2008 Olympic Games; 2010 Shanghai EXPO

Bird Nest

Water Cube

CCTV Tower

China Stadium
Most of these buildings have irregular structures against traditional concept.

Building damages in Sichuan Earthquake

Internal corner damaged
Extruded plan cracked
Setback building damaged
Background

Requirement for the net width of slabs in Chinese code

Area of the hole \( A_1 \)

Area of the slab \( A \)

\[ a_1, a_2 > 2m \]
\[ (a_1+a_2) > 5m \]
\[ (a_1+a_2)L_2 > 0.5 \]
\[ L_2/L_1 > 0.5 \]
\[ A_1/A > 0.5 \]
Background

Requirement for the elevation in Chinese code
Background

Considering the irregularities and complexities of buildings, it is significant to **verify the safety and rationality** of their seismic design through:

- **small scale dynamic model tests**
- **refined numerical analysis**
- **large scale joint tests**
Background

The common practice in China will be:

- Preliminary analysis
- Review Panel
  - Shaking table test
  - Test of weak joint
  - Further analysis
Introduction
The target building

- Zhoushan Eastern Port Business Center (ZEPBC)
- Office building
- A multi-tower building connected by a long-span corridor at the top
- “Round-sky-and-square-earth” concept in the Chinese tradition
Introduction

Structural system

- Two towers: 18 stories; 81m
- Connecting corridor: 58m
Introduction

Structural system

1# Tower

2# Tower
Introduction

Structural irregularities

In the plan layouts

❖ #1 Tower: large openings are over 30% of the floor area in six consecutive stories;

❖ Connecting truss: the span is 58m and it locates at 68m above the ground.

In the elevation

❖ ZEPBC is an two-tower-connected hybrid structure, China has no experiences to build such a structure connected by a semi-rigid truss.
Introduction

Steel + Concrete = Composite/Hybrid

SRC Column
CFT Column
Hybrid Structure
1. Experiment on five SRC columns
Test Curves
<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>R1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compared Parameter</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Section</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /> <img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_0$</td>
<td>0.69</td>
</tr>
<tr>
<td>$\Delta_y$ (mm)</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
<tr>
<td>$F_y$ (kN)</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
<tr>
<td>$\Delta_u$ (mm)</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
<tr>
<td>$F_u$ (kN)</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
<tr>
<td>$\Delta_{\text{max}}$ (mm)</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
<tr>
<td>$u = \Delta_{\text{max}} / \Delta_y$</td>
<td>Test</td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
</tr>
<tr>
<td></td>
<td>(Analysis-Test)/Test</td>
</tr>
</tbody>
</table>
Hysteretic Model of SRC columns
2. Experiments on SRC Column-beam Joint
Test Setup

Welding

Bolt
Strain of the flange

Strain of the steel bar
3. Experiments on SRC Walls
For **SRC walls**,

\[
V_{u}^{SRCW} = \frac{1}{\lambda - 0.5} \left( 0.04 f_{c} b h_{0} + 0.1N \frac{A_{w}}{A} \right) + 0.8 f_{yv} \frac{A_{sh}}{s} h_{0} + \frac{0.5}{\lambda} f_{a} A_{a}
\]

The dowel action and confinement effect of edge structural steels

For **SRC tubes**, 

\[
V_{u}^{ST} = \frac{1}{\lambda - 0.5} \left( 0.04 \beta_{r} f_{c} b h_{0} + 0.1N \frac{A_{w}}{A} \right) + 0.8 f_{yv} \frac{A_{sh}}{s} h_{0} + \frac{0.5}{\lambda} f_{a} A_{a}
\]

Confined factor of the flange walls to the web walls, use \( \beta_{r} = 1.3 \) here
Shaking Table Test

Shaking table test facilities in recent years

- E-defence shaking able (Japan)
- EU Center shaking table (Europe)
- Shaking table at Montreal Structural Engineering Lab. (Canada)
- Shaking table at UBC Civil Engineering Lab. (Canada, under construction)
- Shaking table at China Academy of Building Research (China)
Shaking Table Test

Shaking table test facilities at Tongji Univ.

- Since 1983
- Table dimension: 4m x 4m
- Maximum payload: 250 kN
- Three-dimensional and six degree-of-freedom motions
- Maximum acceleration: X, ±1.2g; Y&Z, ±0.8g
- Maximum stroke: X, ±0.1m; Y&Z, ±0.05m
- Maximum velocity: X, ±1m/s; Y&Z, ±0.5m/s

By now, over 600 models have been tested on the shaking table of Tongji University.
Shaking Table Test
Building model material

Purpose of experiment

Elastic model
Organic glass

Strength model

copper plates
(Steel structural members)
fine-aggregate concrete
with fine wires
(RC members)
Shaking Table Test

Similitude relationship

\[ m(\ddot{x}(t) + \ddot{g}(t)) + c\dot{x}(t) + kx(t) = 0 \]

\[ S_m (S_\ddot{x} + S_{\ddot{g}}) + S_c S_\dot{x} + S_k S_x = 0 \]

\[ S_\rho S_l^3 (S_a + S_a) \]

Elastic modulus, 0.25

\[ \frac{S_E}{S_\rho \cdot S_a \cdot S_l} = 1 \]

Mass density, 2.5

Length, 1/25

Acceleration, 2.5
# Shaking Table Test

## Similitude relationship

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relationship</th>
<th>Model/prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$S_l$</td>
<td>1/25</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>$S_\sigma$</td>
<td>0.25</td>
</tr>
<tr>
<td>Density</td>
<td>$S_\sigma/(S_\sigma \cdot S_l)$</td>
<td></td>
</tr>
<tr>
<td>Force</td>
<td>$S_\sigma \cdot S_l^2$</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>$S_l^{-0.5} \cdot S_\sigma^{0.5}$</td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>$S_\sigma$</td>
<td></td>
</tr>
</tbody>
</table>
Shaking Table Test

Test program

- 40 accelerometers; 25 displacement transducers;
- 10 strain gauges
- El Centro record from California Imperial Valley earthquake; Pasadena record from California Kern County earthquake; Shanghai artificial accelerogram
- In Chinese code, two-stage-three-level design

<table>
<thead>
<tr>
<th>Frequent level</th>
<th>Basic level</th>
<th>Rare level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic force design</td>
<td></td>
<td>Elastoplastic displacement check</td>
</tr>
</tbody>
</table>

- Zhejiang; Intensity 7; PGA 0.1g
Shaking Table Test

Cracking and Failure Patterns

At the frequent earthquakes

- no visible damage

At the basic earthquakes

- 1# Tower cracked at the RC connecting beam ends
- 2# Tower remained undamaged.
- Connecting corridor worked well.
Shaking Table Test
Cracking and Failure Patterns

At the rare earthquakes

- **1# Tower**: more cracks spread at the coupling beam ends.
- **#2 Tower and the connecting truss**: no damages were observed.
Shaking Table Test
Cracking and Failure Patterns

At the rare earthquakes of intensity 8

- **1# Tower**: more cracks spread at the coupling beam ends.
- **1# & 2# Towers**: New cracks were found on the shear walls
- **Connecting truss**: Most members buckled.
Shaking Table Test
Cracking and Failure Patterns

well

Crack at the basic level

buckle

Crack at the rare level of intensity 8
<table>
<thead>
<tr>
<th>Dynamic property</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor level</td>
<td>Frequency (Hz)</td>
<td>0.496</td>
<td>0.496</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>0.496</td>
<td>0.447</td>
</tr>
<tr>
<td></td>
<td>Variation of frequency(%)</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>Variation of stiffness(%)</td>
<td>0</td>
<td>-19</td>
</tr>
<tr>
<td>Moderate level</td>
<td>Frequency (Hz)</td>
<td>0.447</td>
<td>0.447</td>
</tr>
<tr>
<td></td>
<td>Variation of frequency(%)</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>Variation of stiffness(%)</td>
<td>-19</td>
<td>-19</td>
</tr>
<tr>
<td>Major level</td>
<td>Frequency (Hz)</td>
<td>0.347</td>
<td>0.397</td>
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<tr>
<td></td>
<td>Variation of frequency(%)</td>
<td>-30</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>Variation of stiffness(%)</td>
<td>-51</td>
<td>-36</td>
</tr>
<tr>
<td>(intensity 8)</td>
<td>Frequency (Hz)</td>
<td>0.248</td>
<td>0.298</td>
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<tr>
<td></td>
<td>Variation of frequency(%)</td>
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<tr>
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<td>Variation of stiffness(%)</td>
<td>-75</td>
<td>-64</td>
</tr>
<tr>
<td>Vibration modes</td>
<td>Vibration modes</td>
<td>Translation in Y</td>
<td>Translation in X</td>
</tr>
</tbody>
</table>
Shaking Table Test
Experimental displacement

(a) Direction X  (b) Direction Y
Shaking Table Test

Experimental deflection

The stiffness reduction, due to the existence of the round opening, is obvious especially under the major earthquake level.

Deflection: 175/19=9
PGA: 0.22g/0.035g=6
Conclusions

- **ZEPBC** can resist designed **frequent** earthquakes without damage, resist **basic** earthquakes with some structural cracking and deformation, and resist **rare** earthquakes with some major damage, but without catastrophic collapse.

- The overall **torsion** of the multi-tower connected building is **not** remarkable. When the structure is subjected to minor earthquakes, the maximum inter-story drifts in the directions X and Y are **smaller** than the allowable value of **1/800** according to the Chinese code.
Conclusions

- The connecting truss and the rigid joints between the truss and towers worked well to keep two towers deform together under three earthquake levels, however, the stiffness reduction due to the existence of the round opening is obvious especially under the major earthquake level.
The construction of ZEPBC