Shaking Table Tests of the Cable Tray System in Nuclear Power Plants

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Outline

1. Introduction & Motivation
2. Test Specimen
3. Required Response Spectra and Input Motions
4. Test Results
5. Fragility Analysis
6. Conclusions
Introduction

- After 2011 Fukushima Daiichi incident, concerns about seismic safety of existing NPPs increased significantly.

- **Shaking table tests** is one of the best experimental approaches to evaluate the seismic performance of nuclear facilities.

- In the past 35 years, almost **1,000 shaking table tests performed on NPPs** in Tongji University.

- In addition, **many detailed seismic numerical analysis** on the NPPs and their components have been completed since 1985.

C-shape pipe of heat exchanger (AP1000), 2014  
Pump for residual heat removal, 2014
Relevant Previous Studies

- Wind turbine for cooling towers, 2014
- Embedded HALFEN steel channels, 2015
- ABB MNS electrical cabinets, 2016
- Moveable AC power supply, 2016

Some recent shaking table tests of the NPP-related facilities in Tongji Univ.
Relevant Previous Studies

Experimental fast reactor, 1996
NIAH1000 axial floor fan, 2009
LC-PIT2B65/C65(K/S) Elliptical gear flowmeter, 2010

Some numerical analyses of NPP-components in Tongji Univ.
(Courtesy of Prof. Jiang Qian)
Relevant Previous Studies

Seismic numerical analysis of a High Temperature Test Reactor (HTTR)

- Load bearing capacity analysis of main container of HTTR
- Time history analysis of main container of HTTR
- Experimental & analytical results
- Time history analysis of pressure vessel
- Global model of HTTR
- Outer barrel, Internal details
- Courtesy of Prof. Jiang Qian
- FE Model
- Eigen value analysis of secondary pipe & cooling system
- Relevant Previous Studies
  - Eigen value analysis of secondary pipe & cooling system
Motivation

Damage to nuclear facilities including cable trays in past earthquakes

Collapsed cable tray, 1984 Morgan Hill, CA EQ, PGA = 0.50g (Eder & Yanev 1988)

Damaged cable tray system at Sicartsa Steel Mill, 1985 Mexico EQ, PGA = 0.25g (Eder & Yanev 1988)

Damaged conduit at Fertimex Fertilizer Plant, 1985 Mexico EQ, PGA = 0.25g (Eder & Yanev 1988)

Undamaged cable trays at La Villita Power Plant, 1985 Mexico EQ, PGA = 0.15g. Prior to the earthquake, additional vertical supports were added due to excessive dead load sag (Eder & Yanev 1988)

Fukushima Daiichi NPP, 2011
Motivation

Typical types of cable tray systems

The cable tray can be fixed to the ceiling, floor or wall in the NPP. Structurally, there are 3 types of supports: trapeze, L-shaped & cantilever.
Objectives

- Evaluate the seismic response of a full-scale steel cable tray system with shaking table testing
- Compute and evaluate Component Acceleration Amplification (CAA) Factors
- Calculate the damping ratios and natural frequencies for various loading levels
- Develop fragility curves
Test Specimen Construction

Construction process of the ladder type cable tray

- Installing strong beam
- Fabricating steel frame
- Welding the frame to bottom plate
- Connecting the bottom plate to the strong beam
- Installing pallet
- Placing wire cable
Test Specimen Construction

Construction process of the ladder type cable tray

Wire cables in three stories

Typical beam-column joint

Typical pallet-beam joint

Completed specimen
Test Specimen Instrumentation

Total of **15** accelerometers & **8** strain gauges

Sensors on the specimen
Required Response Spectra (RRS) & Input Motions

- Two RRS [to be compared with Test Response Spectra (TRS)]
  - Operating Basis Earthquake (OBE)
  - Safe Shutdown Earthquake (SSE)

- Three artificial input motions for each RRS generated based on code provisions (IEEE 693, 2006; IEEE 344, 2013; CEA, 2015)
  - Duration of motions = 30.0 sec
  - Frequency range: 0.1–100 Hz with 1/3 octave increments
  - Strong motion duration =
    - 20 sec in primary horizontal (X) & vertical (Z) directions
    - 15 sec in secondary horizontal (Y) direction

- Response spectra of generated motions match RRS

3D input motions for OBE

Matched TRS for the OBE
## Required Response Spectra & Input Motions

### Test Procedure

<table>
<thead>
<tr>
<th>Case #</th>
<th>Input Motion</th>
<th>Peak Acc. (g)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; OBE</td>
<td>0.4/0.35/0.33 (X/Y/Z)</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>2</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; OBE</td>
<td>0.4/0.35/0.33 (X/Y/Z)</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>3</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; OBE</td>
<td>0.4/0.35/0.33 (X/Y/Z)</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>4</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; OBE</td>
<td>0.4/0.35/0.33 (X/Y/Z)</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>5</td>
<td>5&lt;sup&gt;th&lt;/sup&gt; OBE</td>
<td>0.4/0.35/0.33 (X/Y/Z)</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>6</td>
<td>SSE</td>
<td>0.80/0.70/0.66</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>7</td>
<td>1.5SSE</td>
<td>1.2/1.05/0.99</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>8</td>
<td>2.0SSE</td>
<td>1.6/1.4/1.32</td>
<td>3D excitation (X/Y/Z)</td>
</tr>
<tr>
<td>9</td>
<td>White noise excitation (with 0.1 g increment)</td>
<td>0.1-1.0</td>
<td>Empty cable tray frame</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.1-1.0</td>
<td>30% loaded</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>0.1-1.0</td>
<td>50% loaded</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>0.1-1.0</td>
<td>70% loaded</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>0.1-1.0</td>
<td>100% loaded</td>
</tr>
</tbody>
</table>

**Load percent**: Actual load of cable in tray with respect to design load (468 kg)

- **5 identical OBEs including white noise**
- **3 levels including white noise with 0.1 g PGA before & after to detect any shift in natural frequencies**
- **5 levels to investigate variation of damping ratio with load percent**
Test Results

- After **5 OBE’s, SSE & 1.5SSE** tests, the cable tray system remained intact.
- After **2.0SSE**, cable **pallets ran out of positions** with left ones have fallen down.
- There were no visible cracks in welded joint but the steel near the joint buckled.

EQ excitation in 2.0SSE (Video clip)

Pallet drop downward

Deformed beam-pallet connection

Buckled steel close to the weld bead
# Test Results

## Component Acceleration Amplification (CAA) factor

\[
0.3 S_{DS} I_p W_p \leq F_p = \frac{0.4 S_{DS} a_p}{R_p / I_p} \left(1 + 2 \frac{z}{h}\right) W_p \leq 1.6 S_{DS} I_p W_p
\]

*F_p*: Seismic design force applied at NC center of gravity, \(I_p\): Component importance factor (1.0 or 1.5), \(W_p\): Component operating weight, \(a_p\): CAA (1.0 to 2.5), \(0.4 S_{DS}\): Mapped design spectral acceleration at short periods, \(z\): Average height of the NCs above grade, \(h\): Average height of roof level above grade, and \(R_p\): Component-response modification factor.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>CAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCE-SEI 7-10/IBC2012</td>
<td>(a_p)</td>
<td>1.0</td>
</tr>
<tr>
<td>UBC1997</td>
<td>(a_p)</td>
<td>2.5</td>
</tr>
<tr>
<td>AIJ 2003</td>
<td>(K_2)</td>
<td>2.0</td>
</tr>
<tr>
<td>EC8 (BS EN 1998-1.2004)</td>
<td>(3/\left(1+(1-T_a/T_i)^2\right))</td>
<td>1.5</td>
</tr>
<tr>
<td>NZS 1170.5:2004</td>
<td>(C(T_p))</td>
<td>2.0</td>
</tr>
<tr>
<td>CSA-S832 2006</td>
<td>(A_r)</td>
<td>1.0</td>
</tr>
<tr>
<td>DGJ08-56-2012</td>
<td>(\zeta_1)</td>
<td>2.0</td>
</tr>
<tr>
<td>BS ISO 13033-2013</td>
<td>(k_{R_p})</td>
<td>1.5</td>
</tr>
</tbody>
</table>

1) The structure is assumed tall with long fundamental period \(T_i\); 2) \(T_a\) or \(T_p = \) fundamental period of the component; 3) EC8 provides a formula to calculate the CAA factor while NZS & CSA provide multi-linear relationships to obtain the CAA factor.

### Experimental CAA factor

<table>
<thead>
<tr>
<th>Dir.</th>
<th>1st OBE</th>
<th>2nd OBE</th>
<th>3rd OBE</th>
<th>4th OBE</th>
<th>5th OBE</th>
<th>SSE</th>
<th>1.5SSE</th>
<th>2.0SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>3.52</td>
<td>3.30</td>
<td>3.36</td>
<td>3.33</td>
<td>3.36</td>
<td>2.94</td>
<td>2.61</td>
<td>2.17</td>
</tr>
<tr>
<td>Y</td>
<td>2.49</td>
<td>2.59</td>
<td>2.59</td>
<td>2.62</td>
<td>2.59</td>
<td>1.88</td>
<td>1.54</td>
<td>1.27</td>
</tr>
<tr>
<td>Z</td>
<td>1.50</td>
<td>1.51</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
<td>1.24</td>
<td>1.16</td>
<td>1.08</td>
</tr>
</tbody>
</table>

- **CAA in X direction** was the **largest** because total stiffness in this direction was the largest.

- **CAA in Z direction** was the **smallest** because vertical stiffness was the smallest.

- **Experimental CAA factors** were **larger** than those from current codes, e.g. CAA=1.0 from ASCE 7-10. Controlling CAA factors in primary & secondary horizontal and vertical directions of the cable tray were **3.52, 2.62 & 1.51**, respectively.
Test Results

Component Acceleration Amplification (CAA) factor

- UBC1997
- NZS, DGJ08
- EC8, BS ISO
- ASCE 7-10, CSA-S832
Test Results

Stress Response

- Peak stresses smaller than design stress in OBE, SSE & 1.5SSE excitations.

- In 2.0SSE, stress response showed **nonlinear behavior** with peak value larger than design stress.

Buckled steel close to the weld bead
Test Results

Natural Frequencies

- **Fundamental frequencies** of the empty cable frame from smallest white noise intensity were 6.64 & 10.03 Hz in primary & secondary horizontal directions, respectively.

- Slight **nonlinear** response occurred in the case of **100% loading** as deduced from the **reduction** of the **fundamental frequency** with increasing peak acceleration.

### Fundamental frequency of cable tray (Hz)

<table>
<thead>
<tr>
<th>Loading ratio</th>
<th>Dir.</th>
<th>Peak acceleration from white noise (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>0%</td>
<td>X</td>
<td>6.64</td>
</tr>
<tr>
<td>30%</td>
<td></td>
<td>5.74</td>
</tr>
<tr>
<td>50%</td>
<td></td>
<td>5.40</td>
</tr>
<tr>
<td>70%</td>
<td></td>
<td>4.98</td>
</tr>
<tr>
<td>100%</td>
<td>X</td>
<td>4.85</td>
</tr>
<tr>
<td>0%</td>
<td>Y</td>
<td>8.46</td>
</tr>
<tr>
<td>30%</td>
<td></td>
<td>8.11</td>
</tr>
<tr>
<td>50%</td>
<td></td>
<td>7.52</td>
</tr>
<tr>
<td>70%</td>
<td></td>
<td>7.22</td>
</tr>
<tr>
<td>9.3%</td>
<td></td>
<td>7.22</td>
</tr>
</tbody>
</table>
Test Results

Damping Ratio

Linear regression to determine relationship between damping ratio & input floor acceleration.

AP1000 (NPP by Westinghouse Electric Co.) overestimates damping ratios especially in X direction.
Fragility Analysis

Probability of failure $p_f$ for a given floor acceleration $a$ in terms of total variability $\beta_c$ (EPRI, 2002):

$$p_f = \Phi \left( \frac{1}{\beta_c} \ln \left( \frac{a}{A_m} \right) \right)$$

$$\beta_c = \sqrt{\beta_R^2 + \beta_U^2}$$

$${A_m} = \frac{TRS_C}{RRS_C} F_D F_{RS} PFA$$

$\Phi$: Cumulative standard normal distribution; $\beta_R$ & $\beta_U$: Logarithmic standard deviations of acceleration to address randomness & uncertainty; $TRS_C$ & $RRS_C$: Clipped test & required response spectra; $F_D$: Capacity factor; $F_{RS}$: Structural response factor = 1.1 (EPRI) or using CAA from test results

<table>
<thead>
<tr>
<th>Factor</th>
<th>OBE</th>
<th>SSE</th>
<th>1.5SSE</th>
<th>2SSE</th>
<th>Choun et al. (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{RS}$ (CAA)</td>
<td>3.56</td>
<td>2.94</td>
<td>2.61</td>
<td>2.17</td>
<td>—</td>
</tr>
<tr>
<td>$F_D$</td>
<td>1.4</td>
<td>1.9</td>
<td>1.2</td>
<td>1.6</td>
<td>—</td>
</tr>
<tr>
<td>$PFA$</td>
<td>0.4</td>
<td>0.8</td>
<td>0.09</td>
<td>0.32</td>
<td>0.22</td>
</tr>
<tr>
<td>$\beta_R$</td>
<td>0.09</td>
<td>0.32</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\beta_U$</td>
<td>0.22</td>
<td>0.28</td>
<td>0.41</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

$PFA$: Peak Floor Acceleration as intensity measure (not EDP: Engineering Demand Parameter)
Conclusions

- The full cable tray (100% loading) behaved elastically in the five OBEs & 1.5SSE excitations → the seismic performance of the cable tray satisfied the code requirements.

- In 2.0SSE excitation, the pallets of the cable tray moved downward from their original positions and buckling damage occurred at the bottom of the column.

- The cable tray frame maintained the load carrying capacity without collapse during application of large earthquake excitations of 1.5SSE & 2.0SSE.

- The experimental CAA factor is larger than that given by some of current code specifications.

- CAA values for 3 vibration directions should be provided in codes, instead of only one value.

- In the longitudinal (X) direction, observed damping ratios were smaller than code provisions.

- In the transverse (Y) direction, observed damping ratios in high loading ratios (30-100%) were close to code provisions. However, some codes overestimated the damping of the cable tray.

- Fragility analysis showed that the component amplification effect should not be ignored as it reflects the dynamic response under earthquake excitation.