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

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B. Huang, W. Lu & K.M. Mosalam (2017), **Shaking Table Tests of the Cable Tray System in Nuclear Power Plants**, *ASCE J. Performance of Constructed Facilities*, In Press.

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

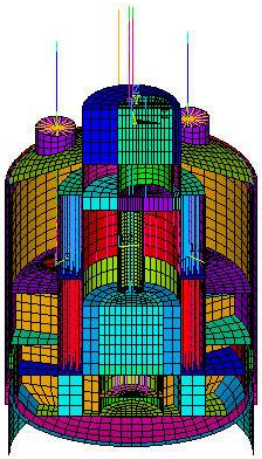
Embedded HALFEN steel channels, 2015

ABB MNS electrical cabinets, 2016

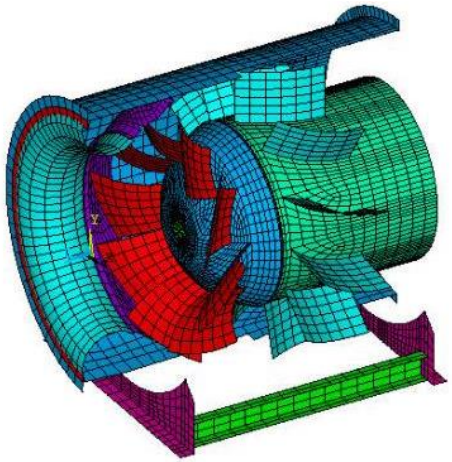
Moveable AC power supply, 2016

Some resent shaking table tests of the NPP-related facilities in Tongji Univ.

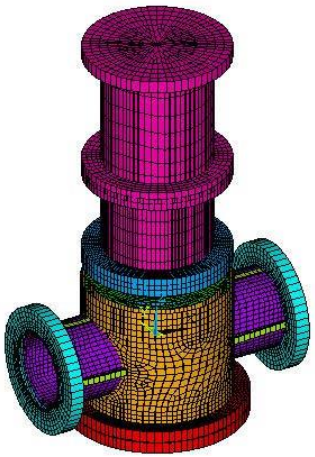
Relevant Previous Studies



Experimental fast reactor, 1996



NIAH1000 axial floor fan, 2009



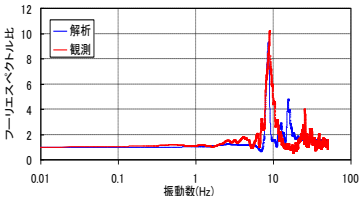
LC-PIT2B65/C65(K/S)
Elliptical gear flowmeter, 2010

Some numerical analyses of NPP-components in Tongji Univ.

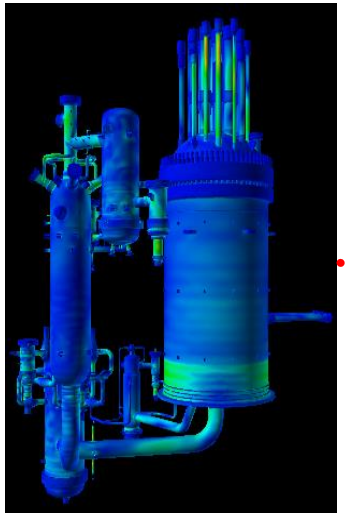
(Courtesy of Prof. Jiang Qian)

Relevant Previous Studies

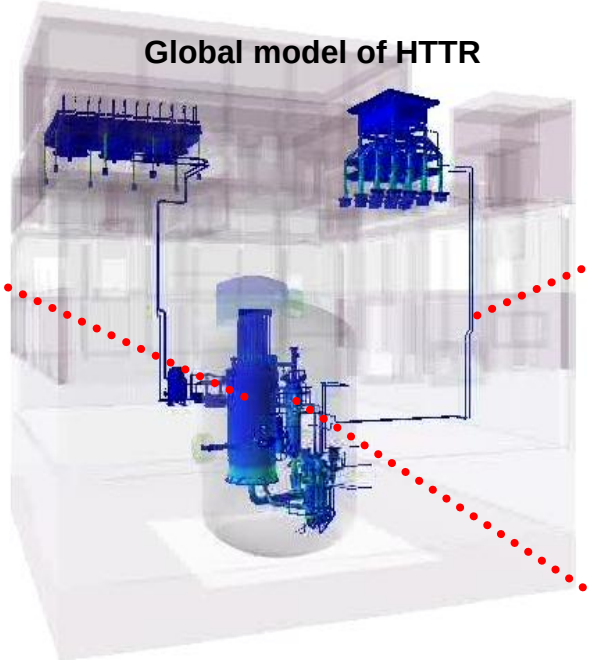
Seismic numerical analysis of a High Temperature Test Reactor (HTTR)



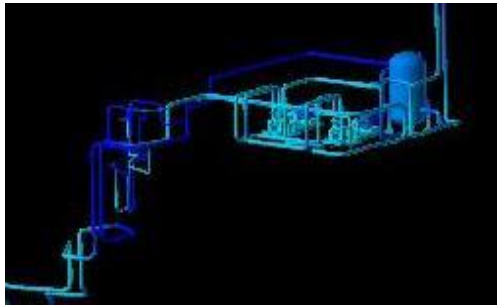
Experimental & analytical results



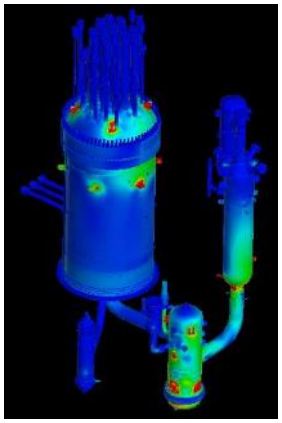
Time history analysis of main container of HTTR



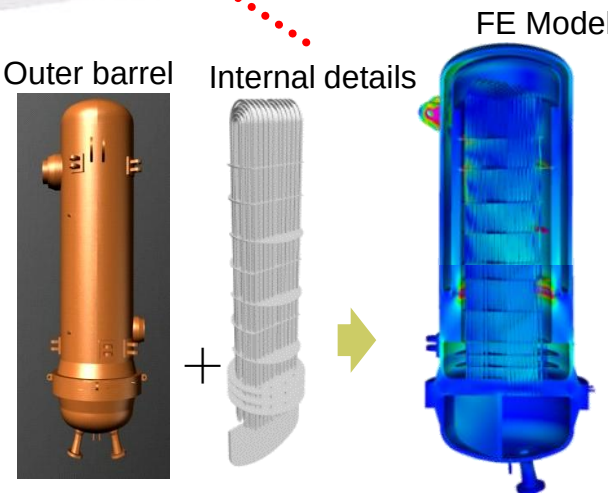
Courtesy of Prof. Jiang Qian



Eigen value analysis of secondary pipe & cooling system



Load bearing capacity analysis of main container of HTTR



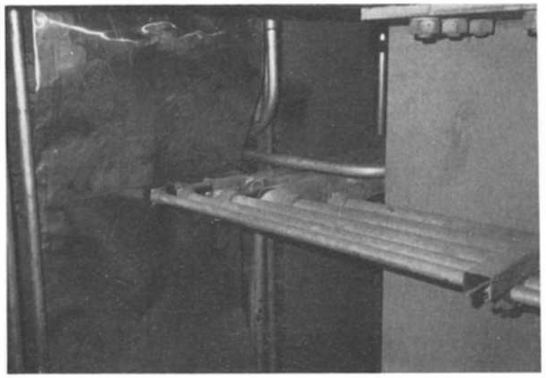
Time history analysis of pressure vessel

Motivation

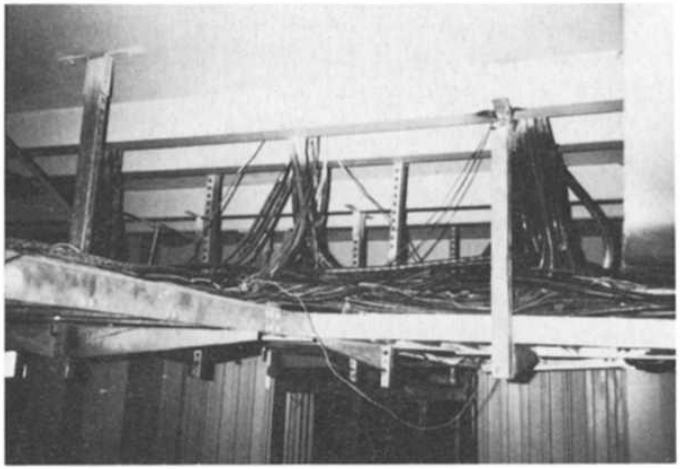
Damage to nuclear facilities including cable trays in past earthquakes

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
https:///www.rt.com/news/339763-disaster-nuclear-earthquake-japan

Motivation

Typical types of cable tray systems

The cable tray can be fixed to the ceiling, floor or wall in the NPP.

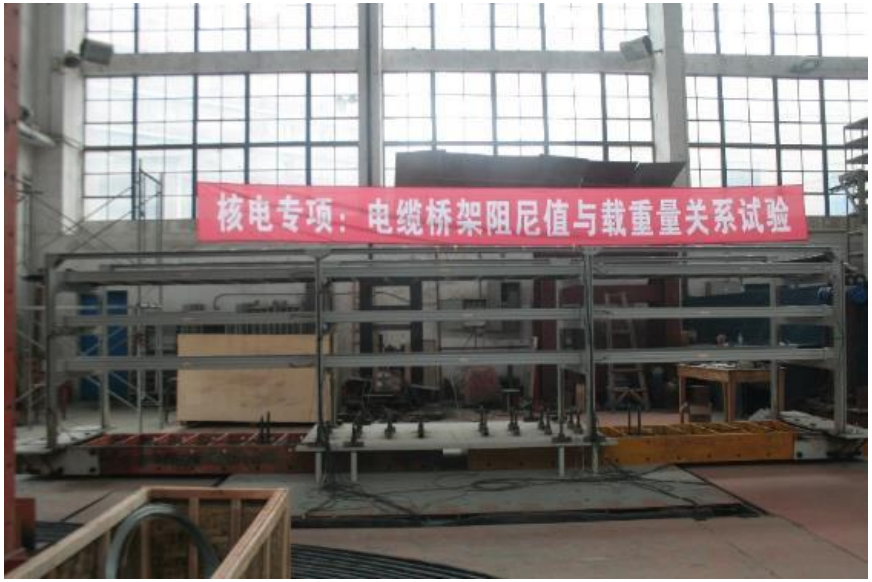
Structurally, there are 3 types of supports: trapeze, L-shaped & cantilever.

Fixed to the floor (Courtesy of X. Liu)

Fixed to the wall (Courtesy of X. Liu)

Fixed to the ceiling

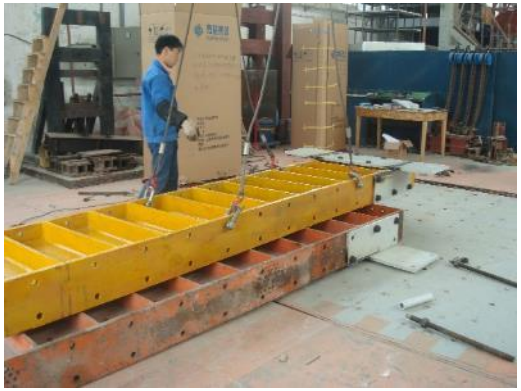
Objectives



- 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

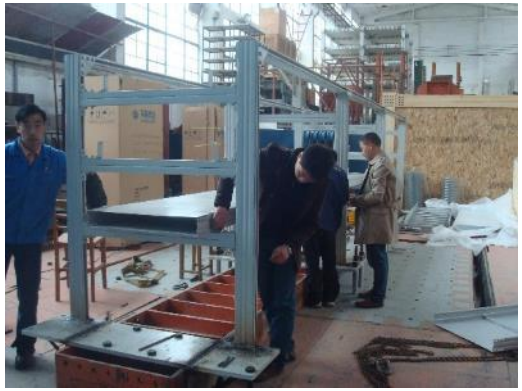


Installing strong beam

Fabricating steel frame

Welding the frame to bottom plate

Connecting the bottom plate
to the strong beam

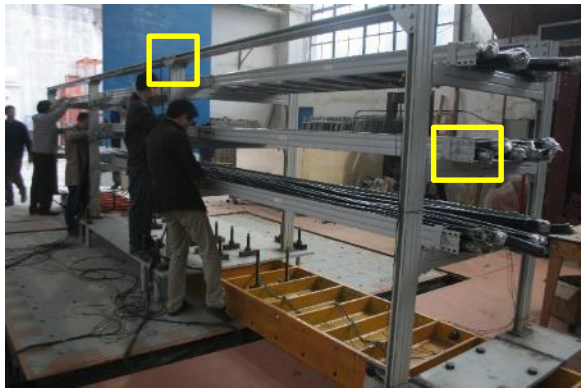


Installing pallet

Placing wire cable

Test Specimen Construction

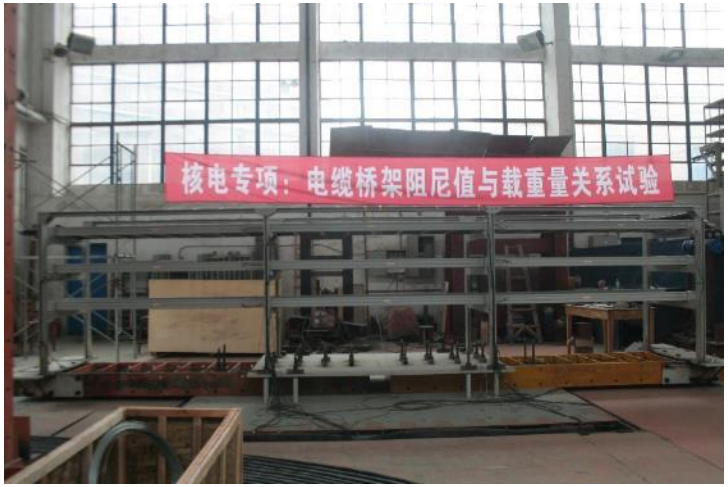
Construction process of the ladder type cable tray



Wire cables in three stories

Typical beam-column joint

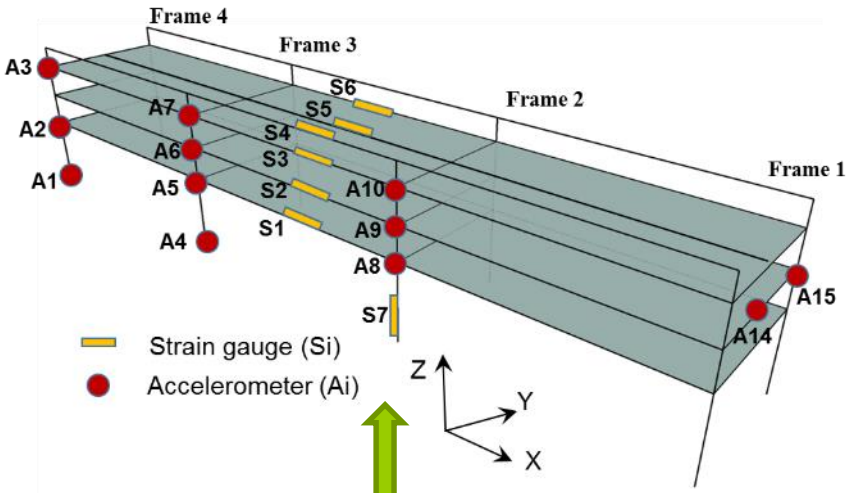
Typical pallet-beam joint

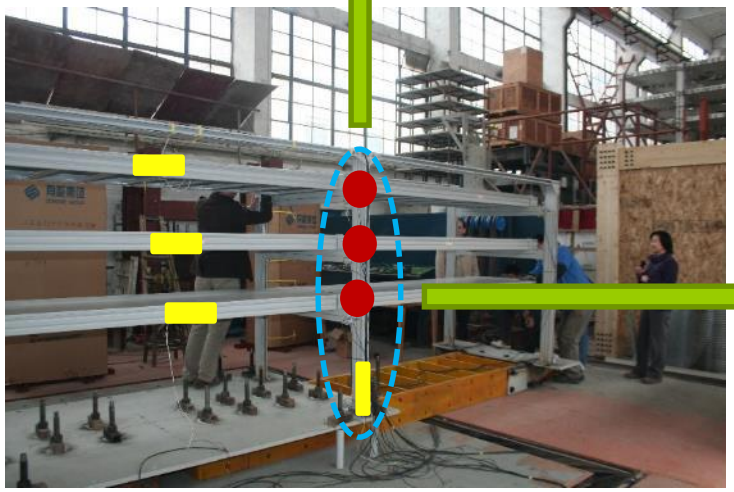


Completed specimen

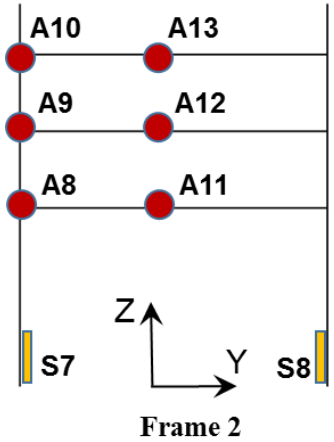
Test Specimen Instrumentation

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

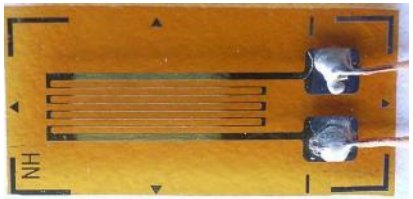




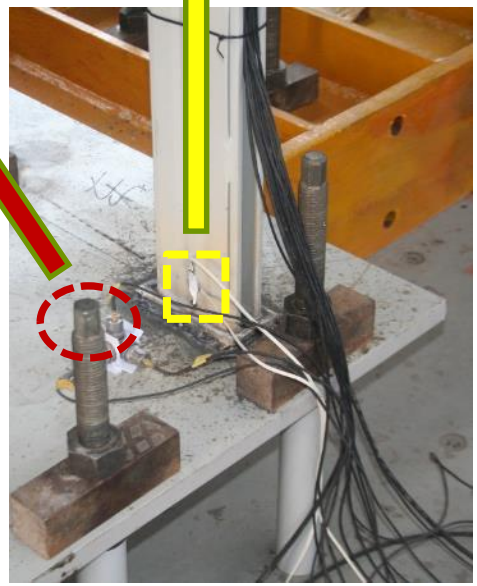
Sensors on the specimen



Accelerometer



Strain gauge

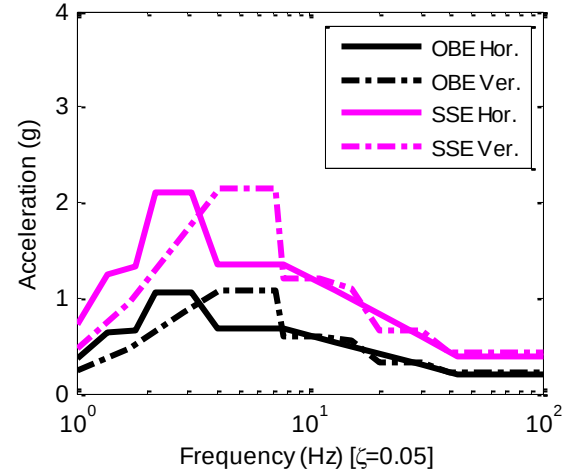


Required Response Spectra (RRS) & Input Motions

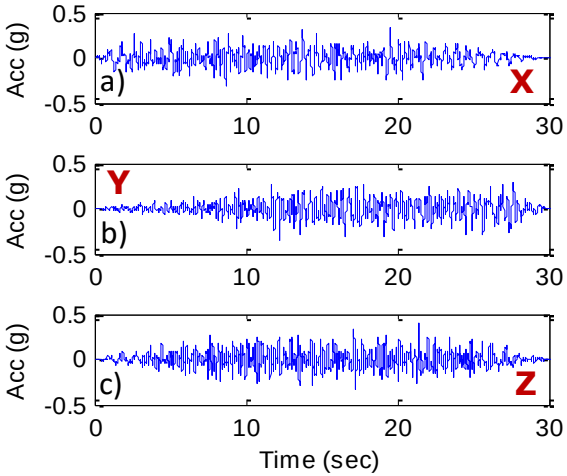
- Two RRS [to be compared with Test Response Spectra (TRS)]
  - Operating Basis Earthquake (OBE)
  - Safe Shutdown Earthquake (SSE)

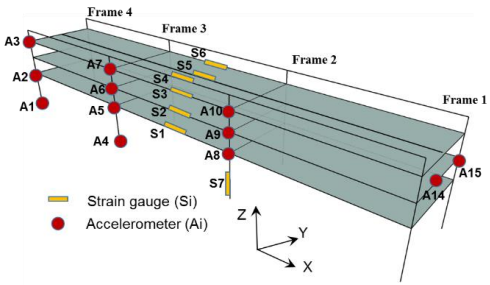
- Three artificial input motions for each RRS generated based on code provisions (IEEE 693, 2006; IEEE 344, 2013; CEA, 2015)
  - Duration of motions = **30.0 sec**
  - Frequency range: **0.1–100 Hz** with 1/3 octave increments
  - Strong motion duration =
    - ✓ **20 sec** in **primary horizontal**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

- Response spectra of generated motions match RRS

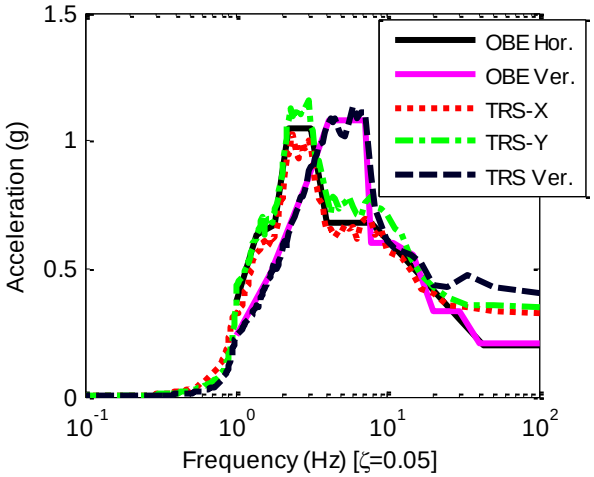


Horizontal & vertical RRS





3D input motions for OBE



Matched TRS for the OBE

Required Response Spectra & Input Motions

Test Procedure

5 identical OBEs including white noise

3 levels including white noise with 0.1g PGA before & after to detect any shift in natural frequencies

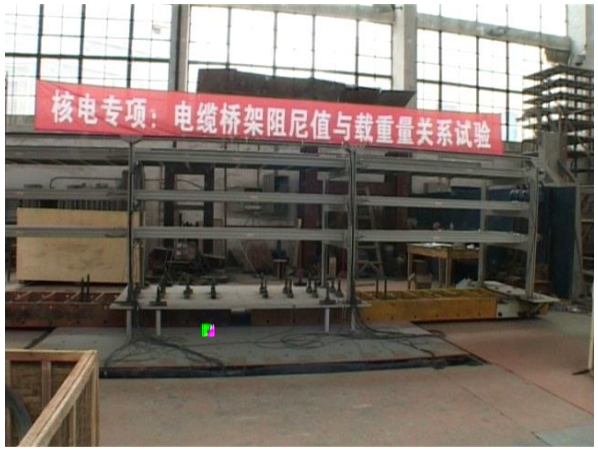
5 levels to investigate variation of damping ratio with **load percent**

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

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

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)

Welded joint before 2.0SSE

Pallet drop downward

Deformed beam-pallet connection

Buckled steel close to the weld bead

Test Results

Component Acceleration Amplification (*CAA*) factor

ASCE 7-10 (2010) $$0.3S_{DS}I_pW_p \le F_p = \frac{0.4S_{DS}a_p}{R_p/I_p}\left(1+2\frac{z}{h}\right)W_p \le 1.6S_{DS}I_pW_p$$

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)**, $0.4S_{DS}$: 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.

Experimental CAA factor

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

- 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.

Code	Description	CAA
ASCE-SEI 7-10/IBC2012	a_p	1.0
UBC1997	a_p	2.5
AIJ 2003	K_2	2.0
EC8 (BS EN 1998-1.2004)	$3/\left(1+(1-T_a/T_1)^2\right)$	1.5
NZS 1170.5:2004	$C_i(T_p)$	2.0
CSA-S832 2006	A_r	1.0
DGJ08-56-2012	ζ_1	2.0
BS ISO 13033-2013	$k_{R,p}$	1.5

1) The structure is assumed tall with long fundamental period T_1; 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.

Code specified CAA factors for nonstructural component (NC)

Test Results

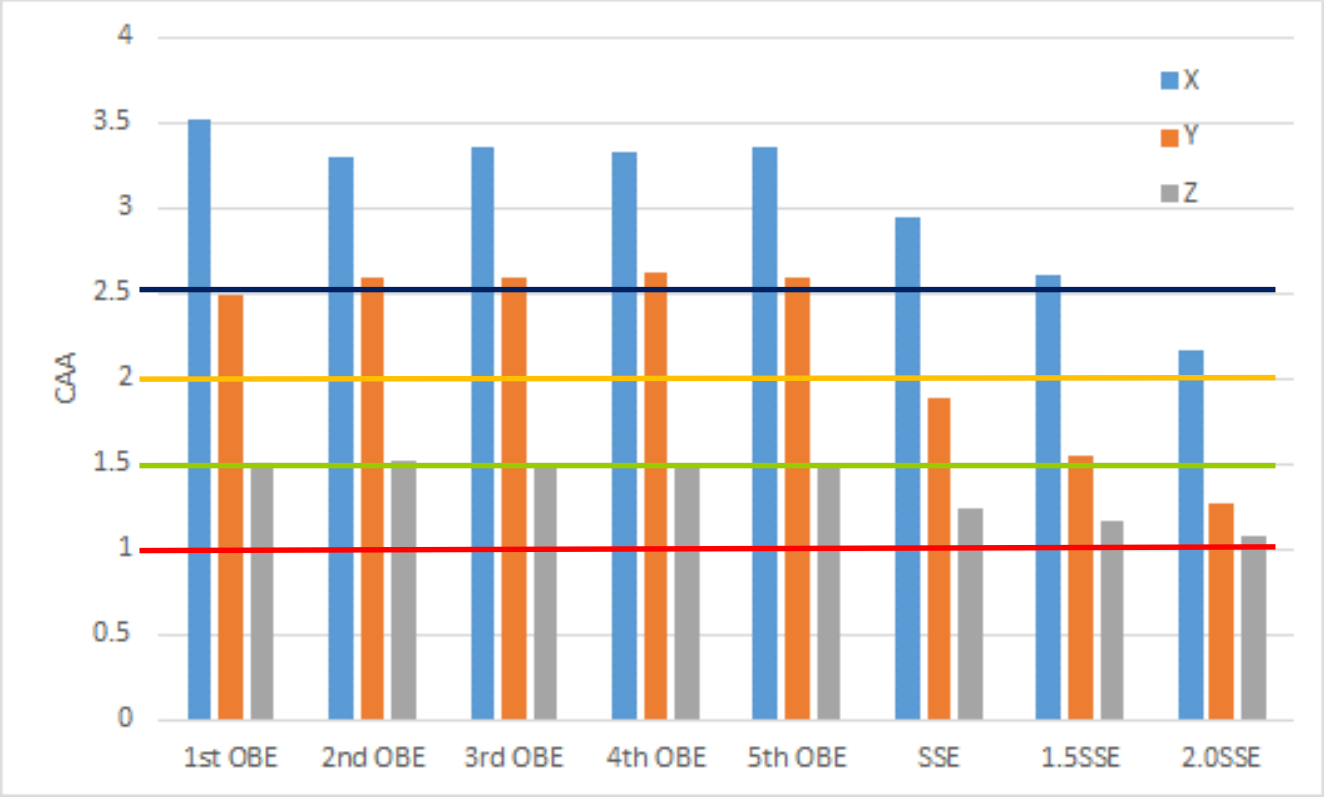
Component Acceleration Amplification (*CAA*) factor

UBC1997

NZS, DGJ08

EC8, BS ISO

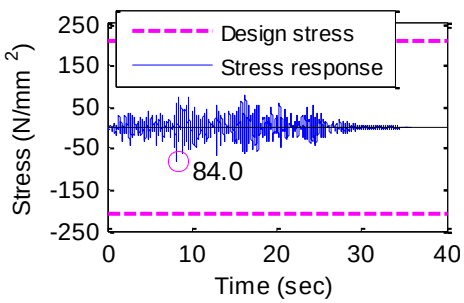
ASCE 7-10, CSA-S832



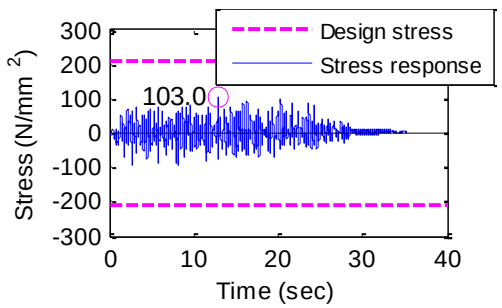
Test Results

Stress Response

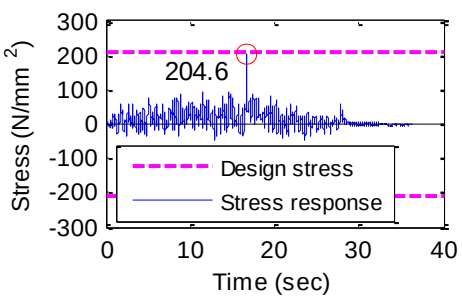
- Peak stresses smaller than design stress in **OBE**, **SSE** & **1.5SSE** excitations.
- In **2.0SSE**, stress response showed **nonlinear behavior** with **peak value larger than design stress.**



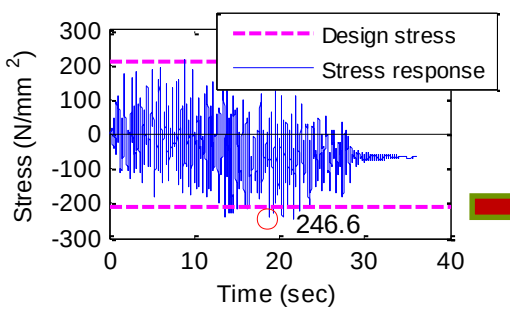
5th OBE



SSE



1.5SSE



2SSE

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.

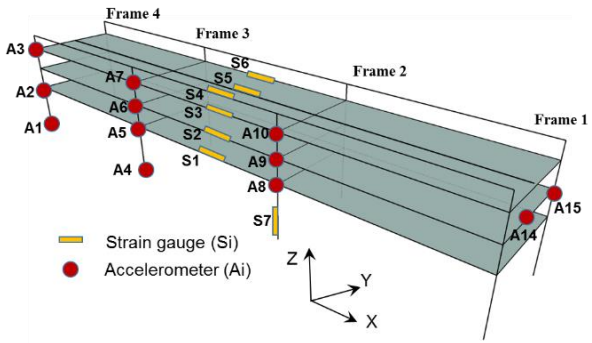
- Slight **nonlinear** response occurred in the case of **100% loading** as deduced from the **reduction** of the **fundamental frequency** with increasing peak acceleration.

Fundamental frequency of cable tray (Hz)

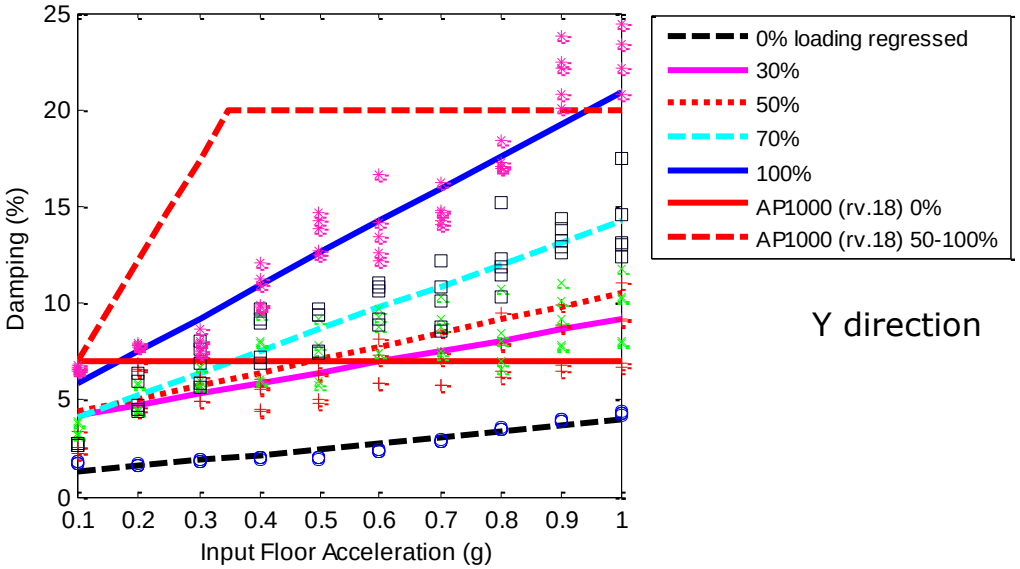
Loading ratio	Dir.	Peak acceleration from white noise (g)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0%	X	6.64	6.59	6.59	6.54	6.51	6.49	6.43	6.36	6.32	6.34
30%		5.74	5.71	5.73	5.68	5.59	5.61	5.55	5.55	5.52	5.48
50%		5.40	5.38	5.34	5.33	5.29	5.24	5.25	5.18	5.17	5.16
70%		4.98	4.95	4.92	4.94	4.88	4.79	4.80	4.81	4.80	4.73
100%	**4.3%**	**4.85**	**4.83**	**4.79**	**4.74**	**4.74**	**4.73**	**4.73**	**4.68**	**4.69**	**4.64**
0%	Y	10.03	9.97	9.97	9.86	9.84	9.70	9.59	9.61	9.46	9.31
30%		8.46	8.34	8.47	8.45	8.50	8.60	8.62	8.60	8.57	8.86
50%		8.11	8.31	8.19	8.05	8.05	7.80	8.03	8.25	8.13	8.10
70%		7.52	7.39	7.54	7.34	7.25	7.26	7.29	7.34	7.25	7.34
100%	**9.3%**	**7.22**	**7.11**	**7.00**	**6.95**	**6.92**	**6.93**	**6.77**	**6.66**	**6.49**	**6.55**

Test Results

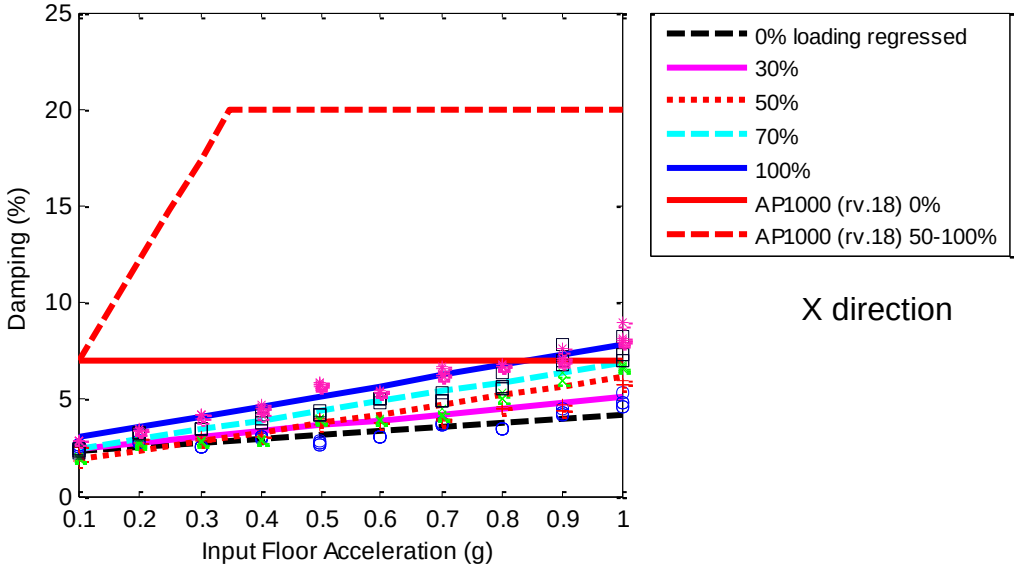
Damping Ratio



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



Y direction



X direction

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

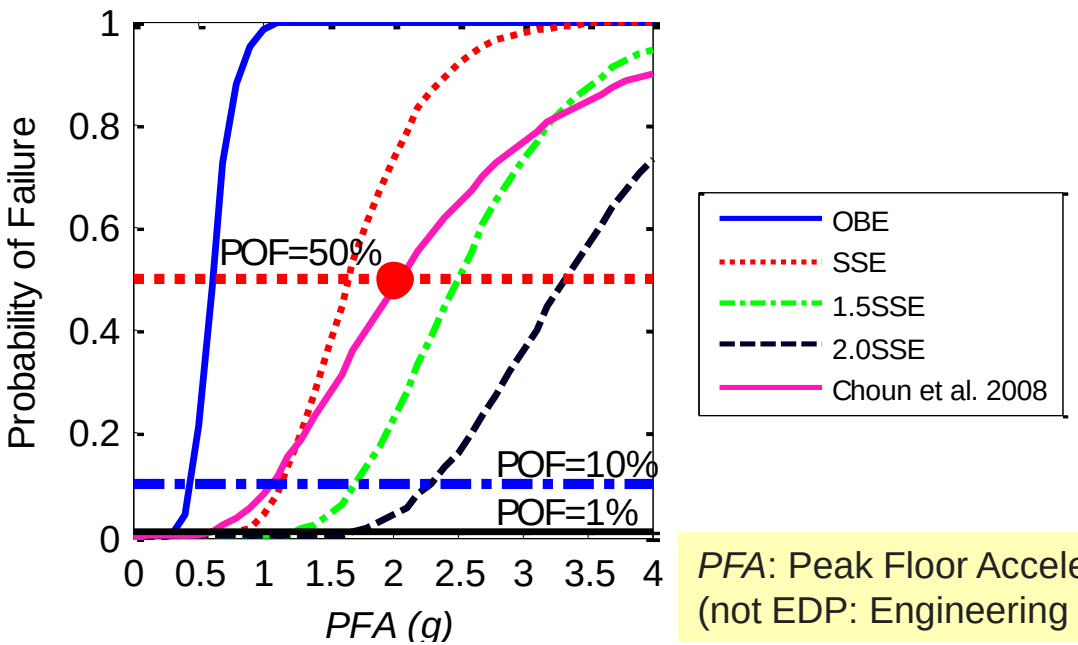
Fragility Analysis

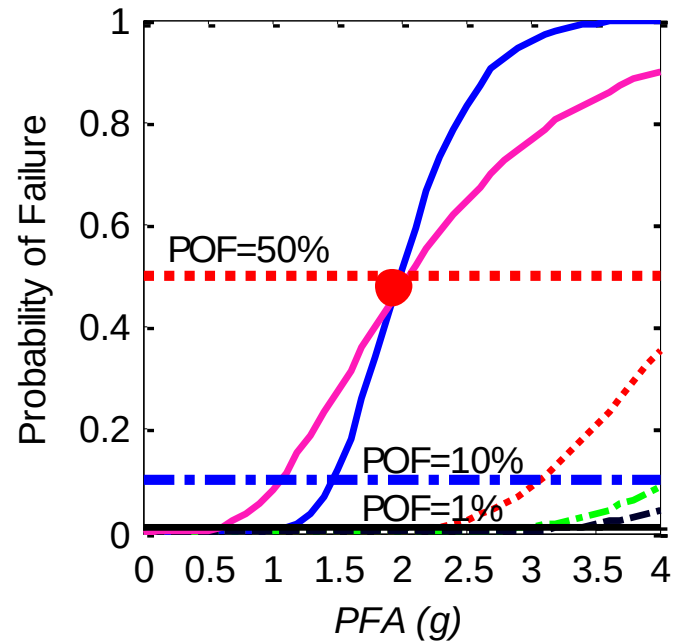
Probability of failure p_f for a given floor acceleration a in terms of total variability β_c (EPRI, 2002):

$$p_f = \Phi\left(\frac{1}{\beta_c}\ln\left(\frac{a}{A_m}\right)\right) \qquad \beta_c = \sqrt{\beta_R^2 + \beta_U^2} \qquad A_m = \frac{TRS_C}{RRS_C} F_D F_{RS} PFA$$

Φ: Cumulative standard normal distribution; β_R & β_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**

Factor	OBE	SSE	1.5SSE	2SSE	Choun et al. (2008)
F_{RS} (CAA)	3.56	2.94	2.61	2.17	—
F_D	1.4		1.9		—
PFA	0.4	0.8	1.2	1.6	—
β_R		0.09			0.32
B_U	0.22		0.28		0.41





Using CAA factors

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.