Lessons Learned from 3D Shake Table Testing of a Full-Scale Seismically-Isolated Building

Keri L. Ryan

Associate Professor, University of Nevada, Reno

Reflections of Career Development and Discovery in Seismic Isolation

Keri L. Ryan

Associate Professor, University of Nevada, Reno

Important Lessons Learned from My Mentor

- ✓ How to write organized technical documents that are polished to perfection, with clarity of expression and conciseness
- ✓ How to approach research systematically
  - ✓ Start at a basic level
  - ✓ Systematic variation of important dynamic parameters
  - ✓ Validate all results by comparison with fundamental engineering principles

Methodical Approach to Research

(1) When you are trying to accomplish something, lay down all possible options that you can think of. Look at what other people have done by exploring literature. Make sure you have been deliberate and careful in your brainstorming, and lay down all possibilities.

(2) Do not make decisions arbitrarily based on a feeling or a whim. You must be able to back up your decisions with concrete information; facts, data, etc.

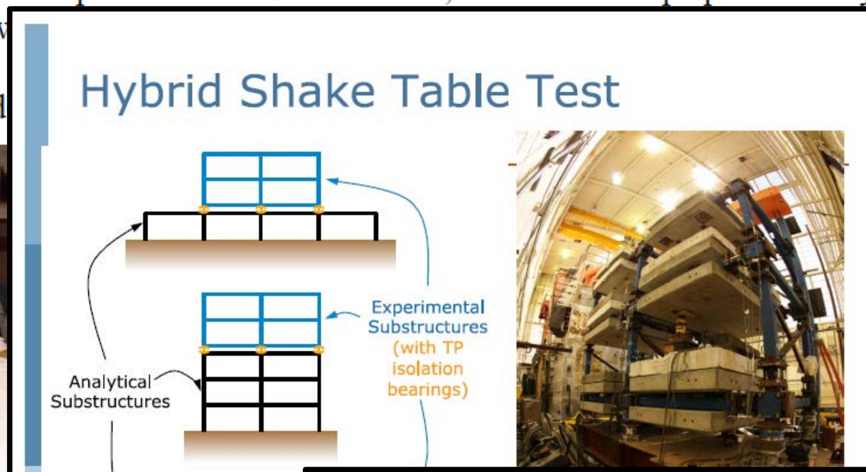
(3) Weigh the data carefully before making a decision. Make sure you have considered each option, and the pros and cons for each before reaching your decision.

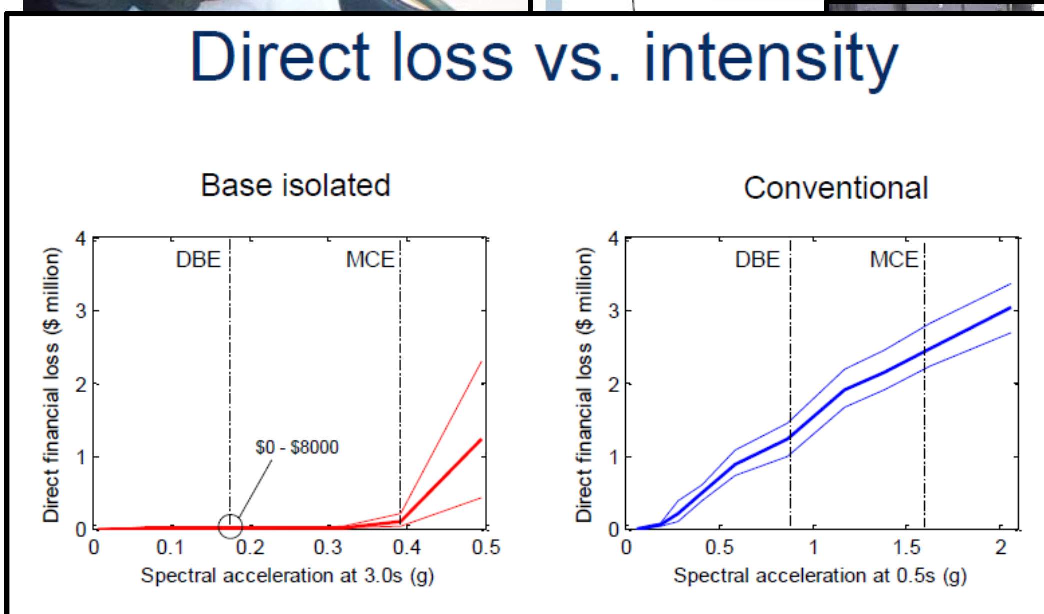
Tools for Isolation and Protective Systems

Addressing Challenges to the Adoption of Seismic Isolation-TIPS Project Workshop November 30, 2007: Burlingame, CA

EXECUTIVE SUMMARY

More than 40 individuals participated in the November 30, 2007 workshop sponsored by the NEES-TIPS Project (NSF Av
range of professions, including
managers, researchers, device vend





NEES TIPS
(Tools for Isolation and Protective Systems)

in collaboration with

E-Defense
(National Institute for Earth Science and Disaster Prevention)

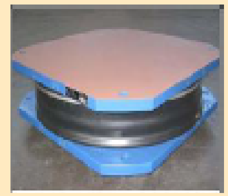
announce

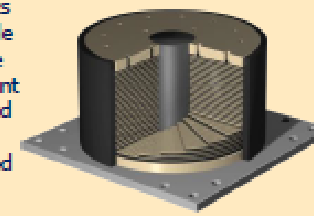
Full Scale Seismic Isolation Test Program

In a collaborative effort between NEES TIPS, NEES Nonstructural, and NIED in Japan, a 5-story steel moment frame building will be shaken under extreme earthquake loading at Hyogo Earthquake Engineering Research Center, commonly known as E-Defense. The specimen will be shaken with seismic isolation systems and in the fixed-base configuration. Additional nonstructural components including interior walls, ceilings, piping, and concrete cladding panels will be constructed for the earthquake tests. The tests will take place 3 week time frame in August 2011, with 6 days of shaking anticipated.

Test Program Objectives

1. Accelerate adoption of protective systems through full scale proof of concept shaking of a seismically isolated frame building.
2. Demonstrate that damage free performance of a building with Triple Pendulum bearings can be attained in an MCE level event in a high seismicity region, through evaluation of the response of the structure, nonstructural components and contents relative to fixed-base configuration.
3. Evaluate performance of an elastomeric isolation system designed to protect a nuclear power plant in beyond design basis shaking.
4. Identify performance limits for extreme motions. Triple Pendulum bearings will be tested to their displacement limits. Sustained axial load capacity of elastomeric bearings beyond calculated limits will be evaluated.





For more information about these devices, please visit http://www.earthquakeprotection.com, http://www.dis-inc.com

Anticipated Shaking Schedule

Test Date	Specimen Configuration	Excitations
August 17	Seismic isolation with Triple Pendulum bearings provided by EPS	Sinusoidal characterization, design, and long duration subduction ground motions
August 18		Excitations representing Maximum Considered Event (MCE)
August 19		Excitations inducing displacement limits in Triple Pendulum bearings
August 24	Seismic isolation with lead rubber bearings and sliders provided by DIS	Excitations representing up to a design basis event for a nuclear power plant
August 26		Excitations representing a beyond design basis event for a nuclear power plant
August 31	Conventional base system	Select excitations representative of frequent, design and MCE level events

A small sample of the test motions that will be run: 1978 Tabas (Tabas Sta.), 1989 Loma Prieta (Los Gatos Pres. Ctr.), 1994 Northridge (Sylmar and Rinaldi Rec. Sta.), 1995 Kobe (Takatori), 1999 Chi-chi (TCU 065), Sannomaru (synthetic long duration subduction motion)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Scope of Tests – 3 Configurations

Isolated with triple friction pendulum (TP) bearings

Isolated with hybrid configuration of lead-rubber and cross-linear bearings

Fixed at the base

Period T = 0.7 sec
First Yield Base Shear ~ 0.67W

Nonstructural Components

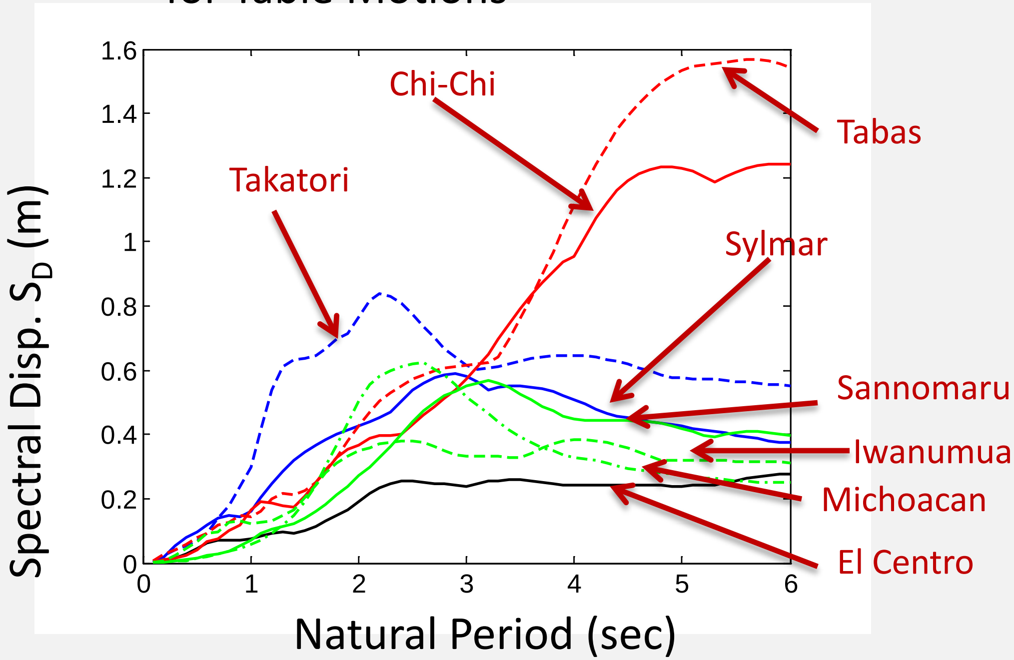
Ceilings and Partitions

Fire Sprinkler Piping

Enclosed contents rooms

The TPB system was to be subjected to a wide variety of ground motions.

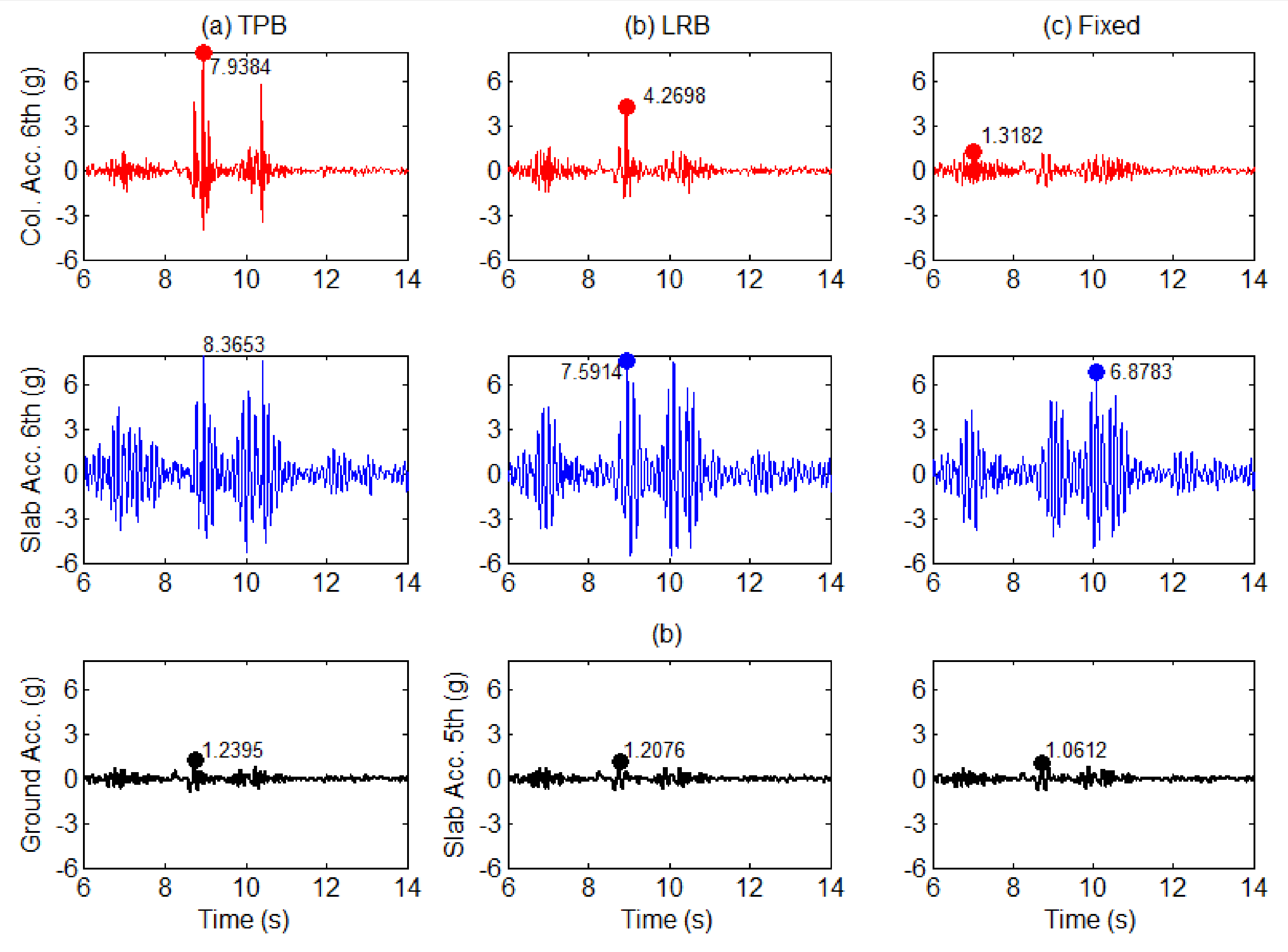
15% Damped Spectral Disp.
for Table Motions



- Typical broadband frequency motion
  - El Centro
- Typical near-fault (2-3 sec pulse)
  - Sylmar (Northridge)
  - Takatori (Kobe)
- Very long period near-fault (4-5 sec pulse)
  - Chichi, Tabas
- Long period, long duration subduction
  - Sannomaru
  - Iwanuma (Tohoku)
- Soft soil record
  - Michoacan (Mexico City)


P3-F, LEFT-TOP

Rinaldi 88% - 3 System Comparison Vertical Acc.

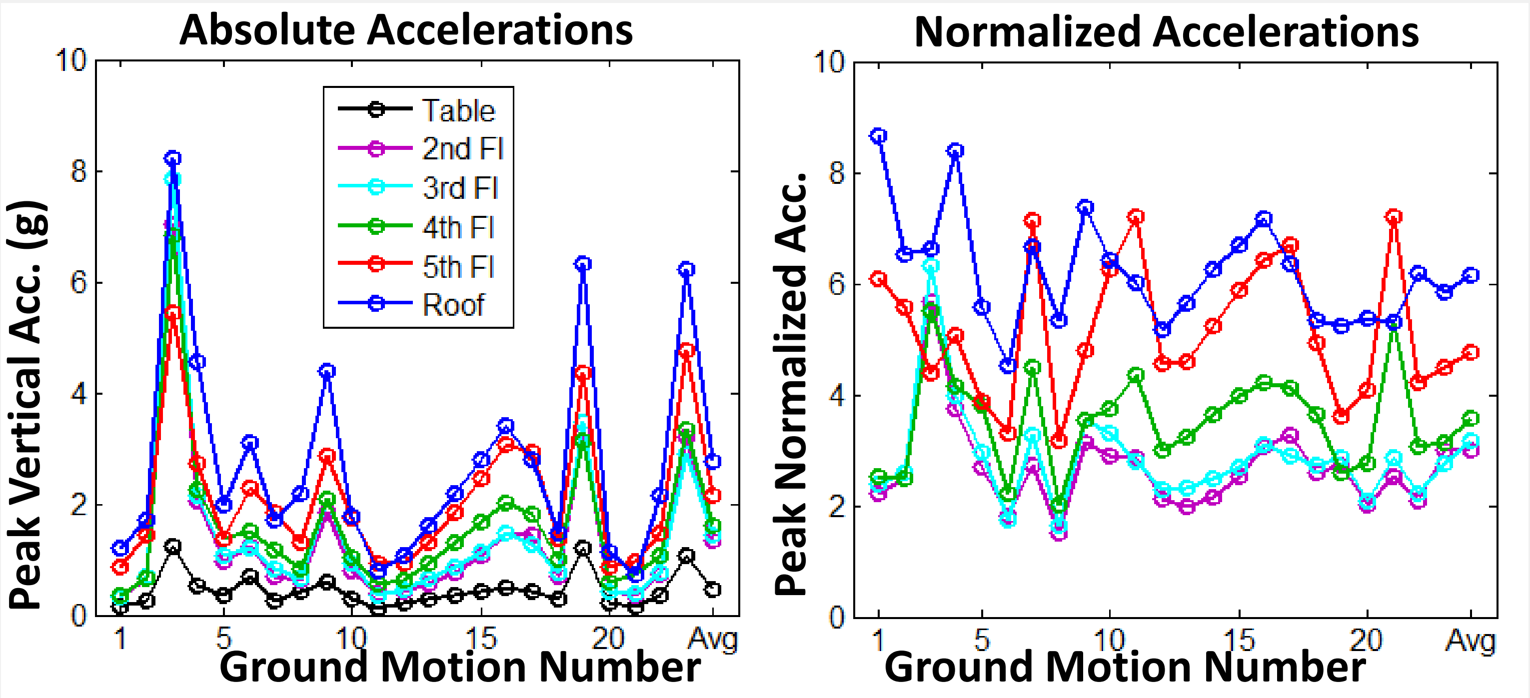


6th floor column

6th floor slab

Shake table (ground)

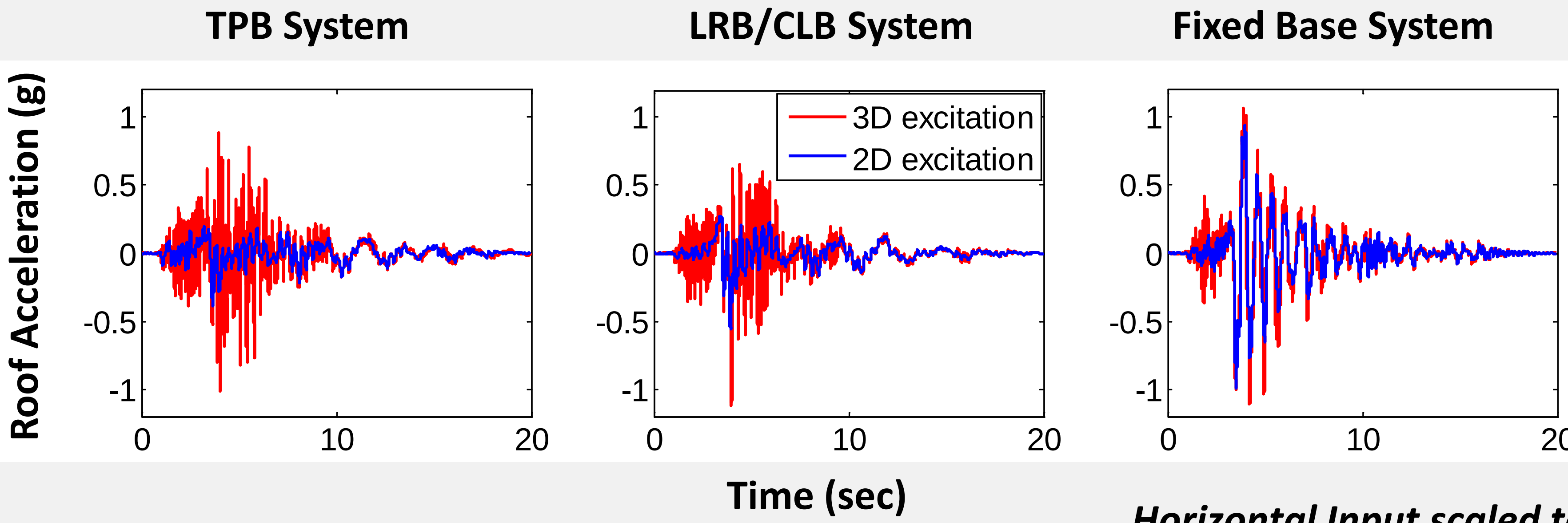
Amplification of peak vertical acceleration from table to floor slabs



- ✓ On average, peak slab acceleration increased up the building height
- ✓ Average amplification factors on the order of 3 to 6

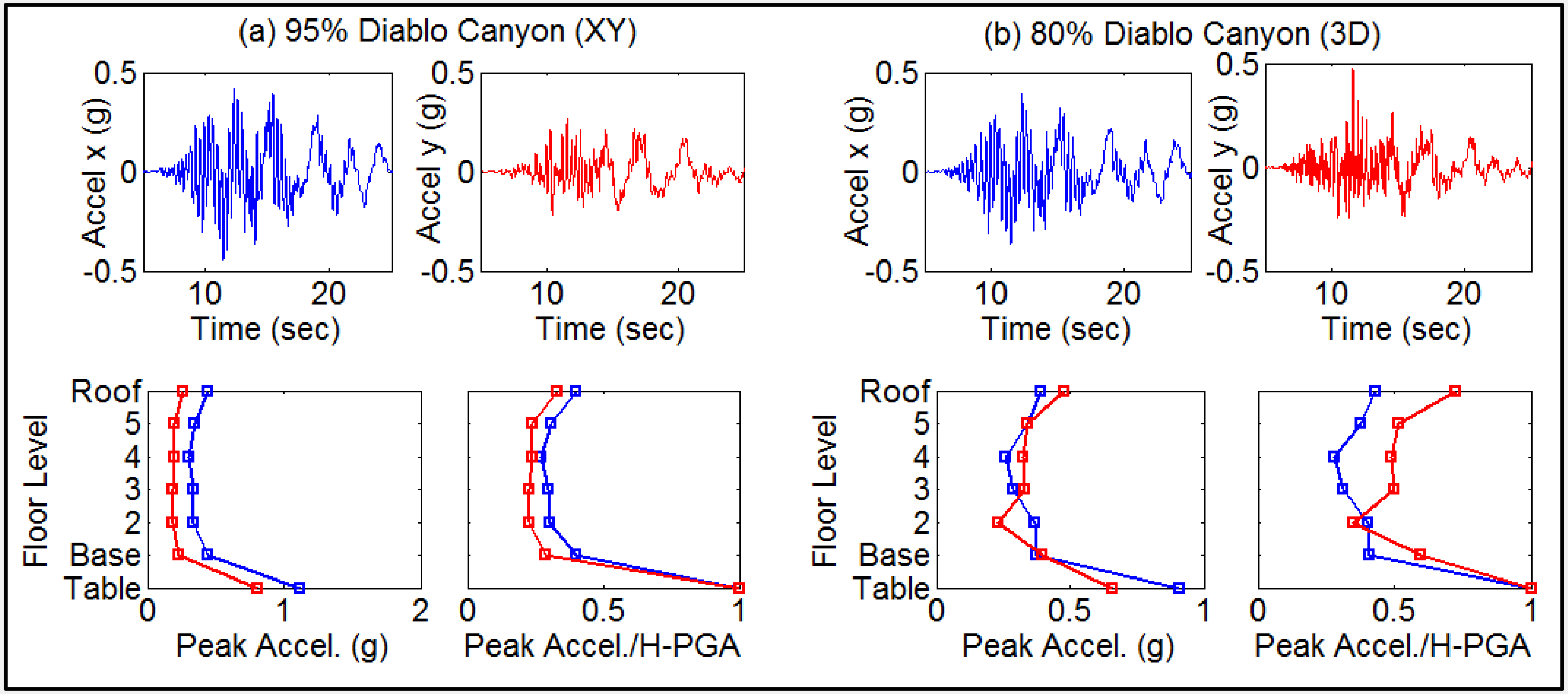
Horizontal accelerations were amplified in 3D shaking compared to 2D shaking, suggesting some a horizontal-vertical coupling effect

Roof Acceleration in Each System Configuration
(Northridge – RRS: Peak Table Acc = 1.14 g horizontal, 1.2 g vertical)



Horizontal Input scaled to 40% on Fixed-Base System

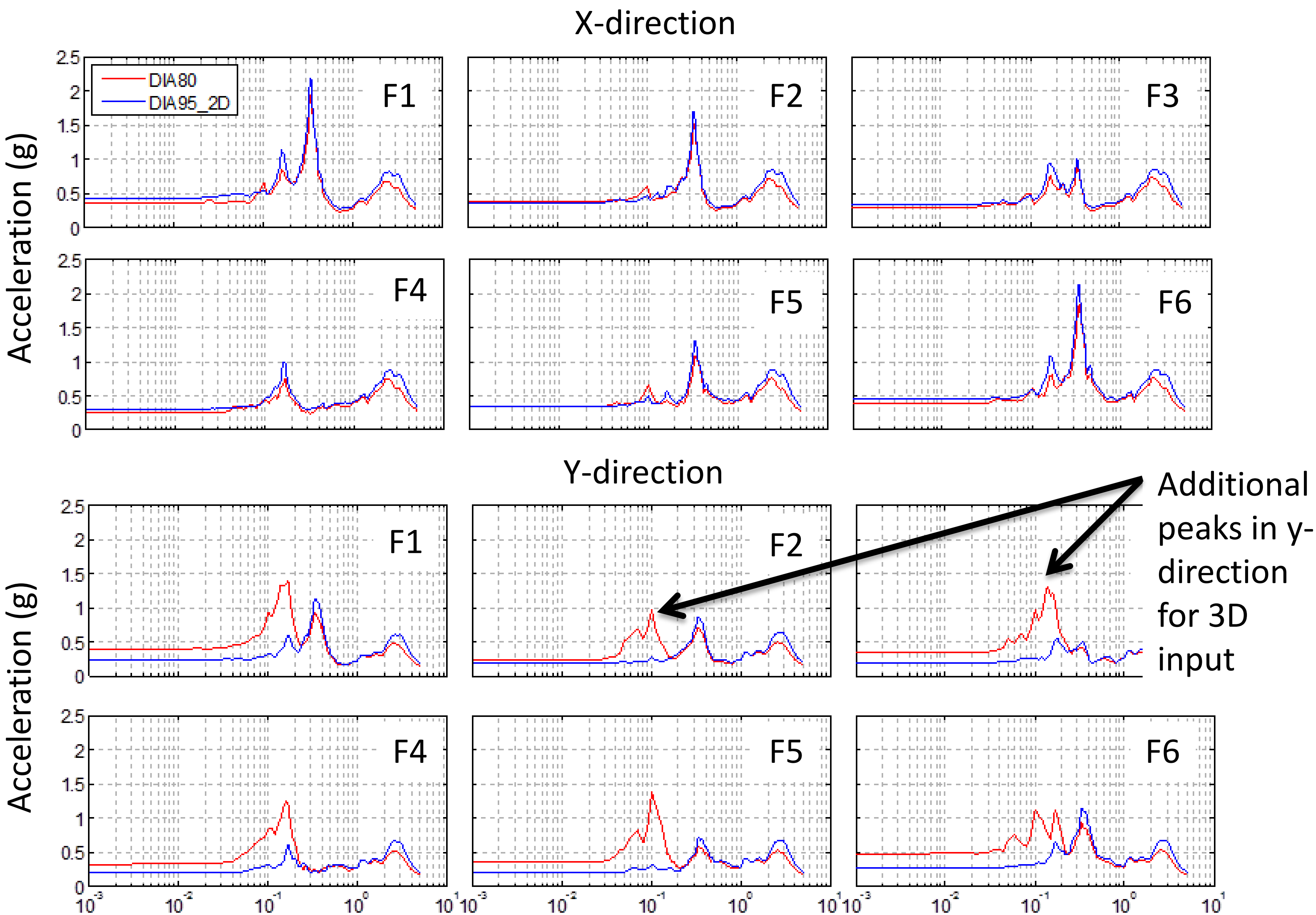
Floor Acceleration Response in Hybrid LRB System, XY vs 3D Motion (Vert. PGA = 0.44g)



Ryan KL, Coria CB, Dao ND (2013). "Large Scale Earthquake Simulation of a Hybrid Lead Rubber Isolation System Designed With Consideration of Nuclear Seismicity", *CCEER Report No. 13-9, Center for Civil Engineering Earthquake Research,* University of Nevada, Reno

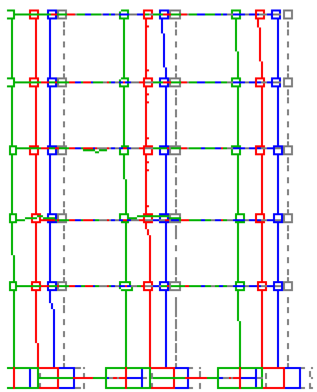
NSF NEES N NIED E-Defense

What was the cause of the increase in horizontal floor acceleration?



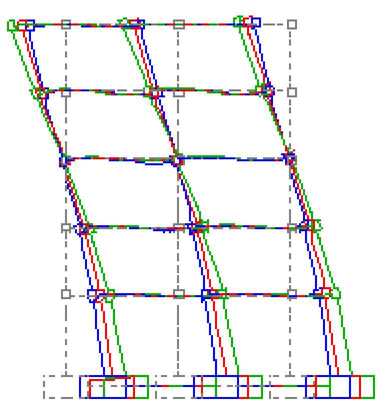
Analysis of Floor Spectra, Hybrid LRB System and XY Input

Mode 1



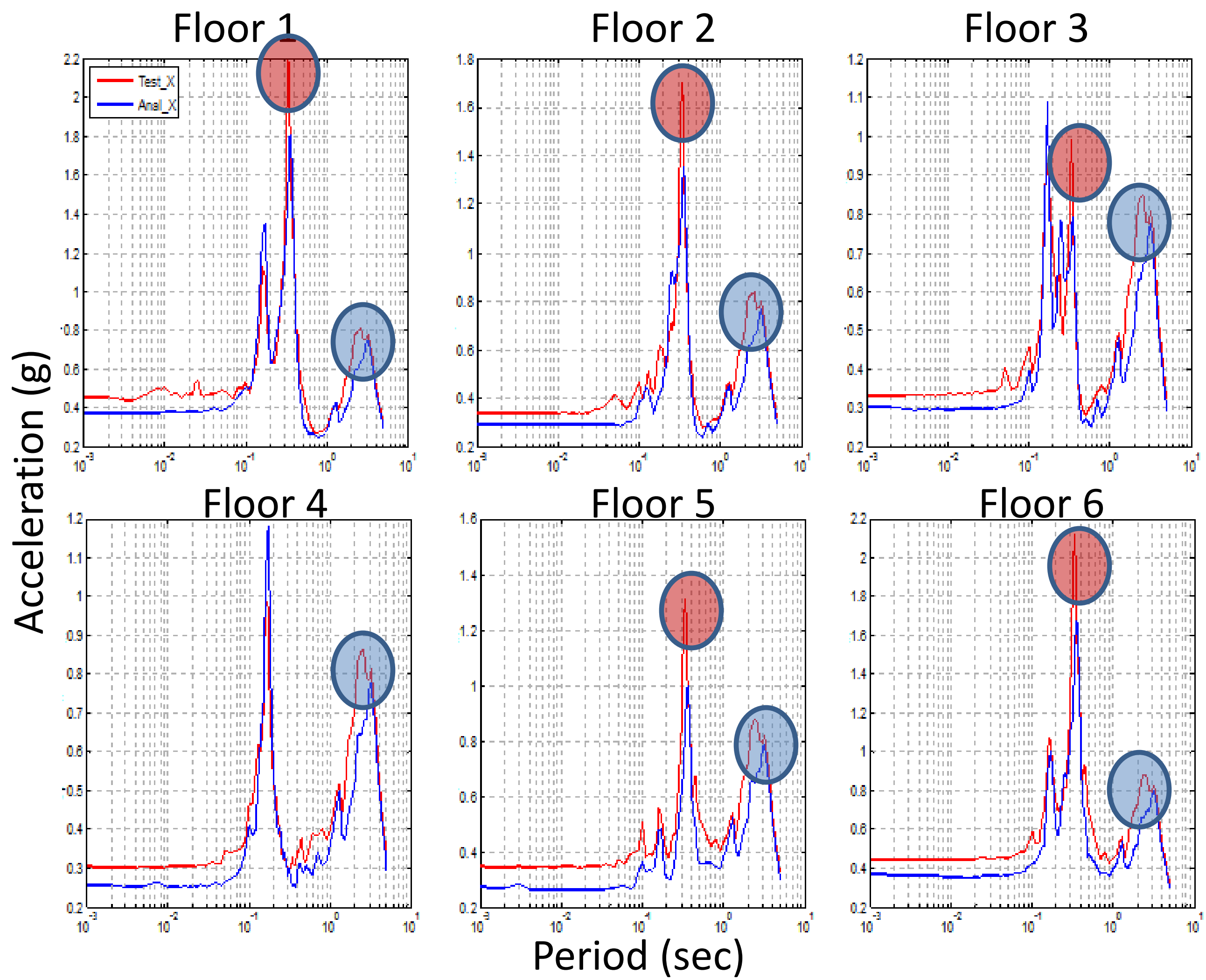
Isolation Mode
T = 2.72 sec

Mode 5



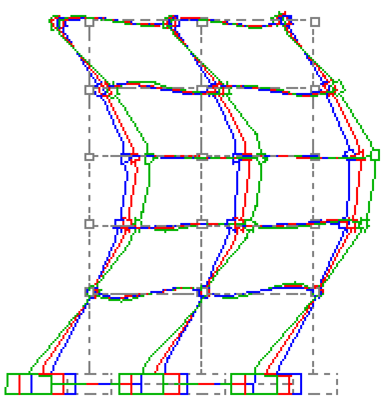
1st Structural Mode
T = 0.36 sec

Floor Spectra for Diablo Canyon 95%, x-direction



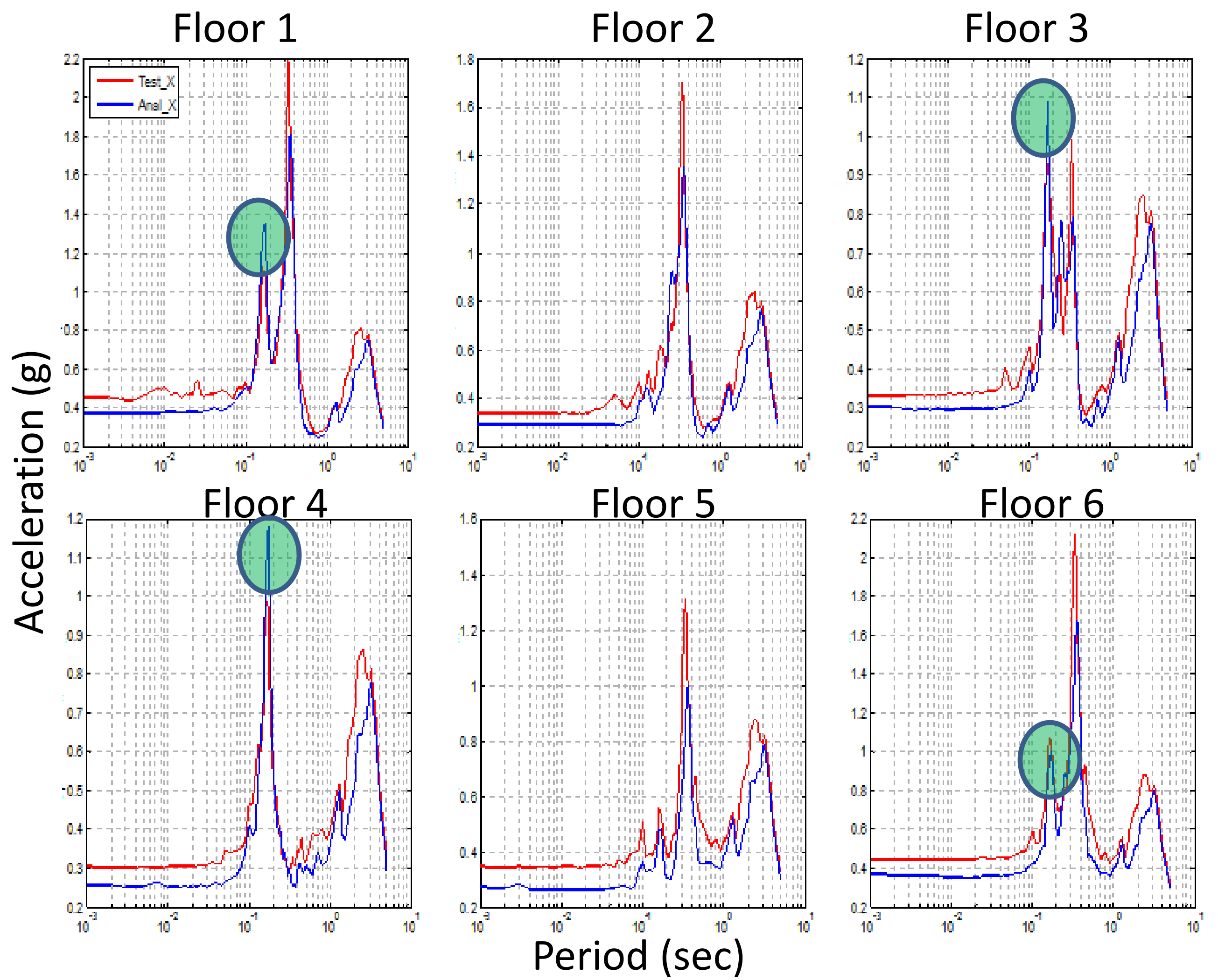
Analysis of Floor Spectra, Hybrid LRB System and XY Input

Mode 8

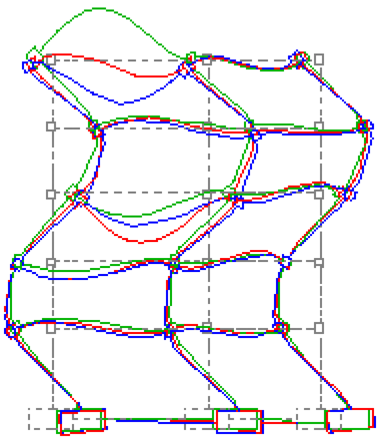


2^{nd} Structural Mode
T = 0.17 sec

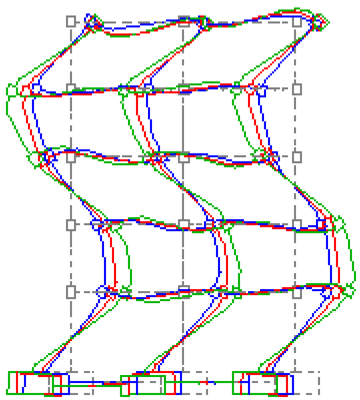
Floor Spectra for Diablo Canyon 95%, x-direction



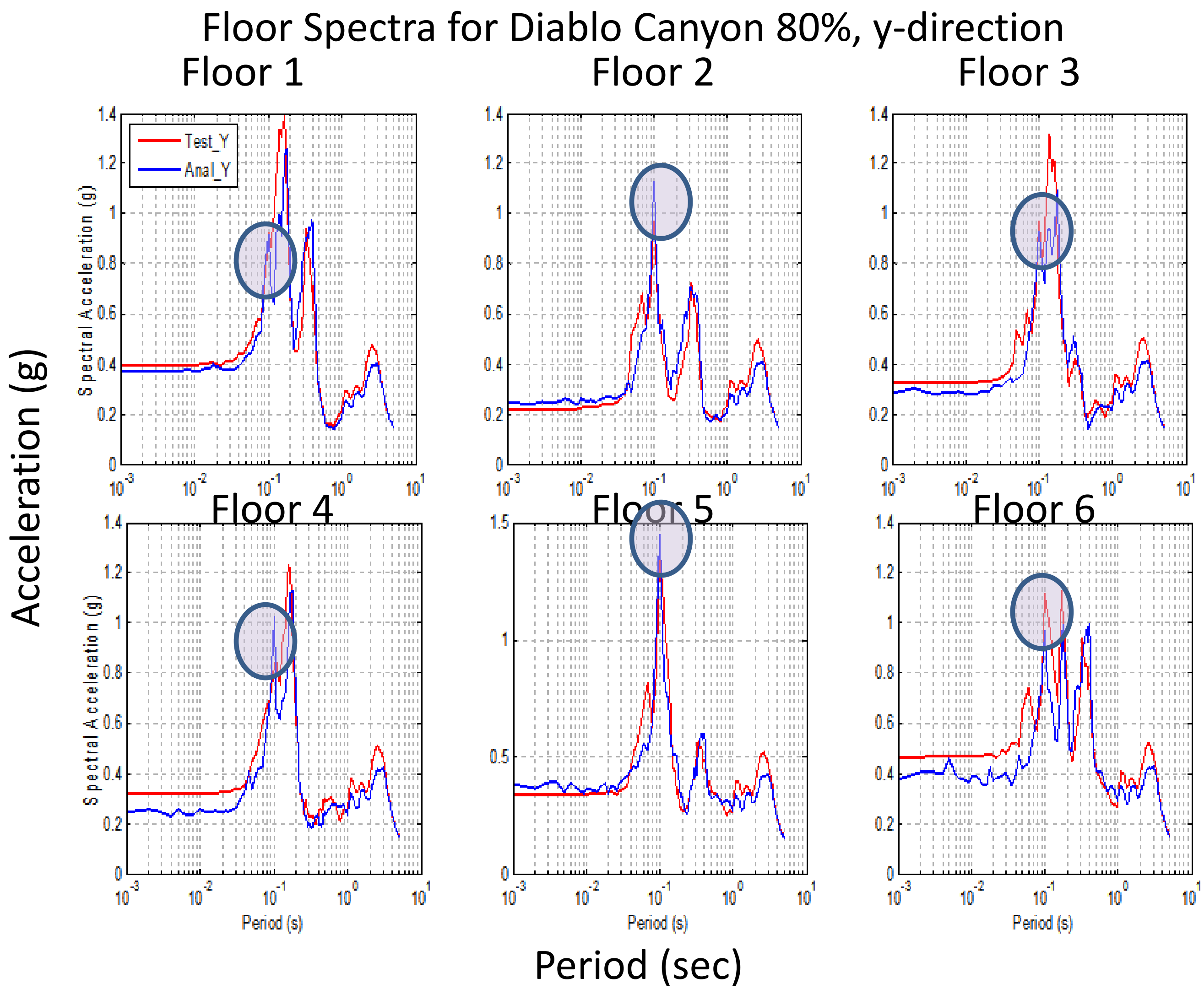
Analysis of Floor Spectra, Hybrid LRB System and 3D Input



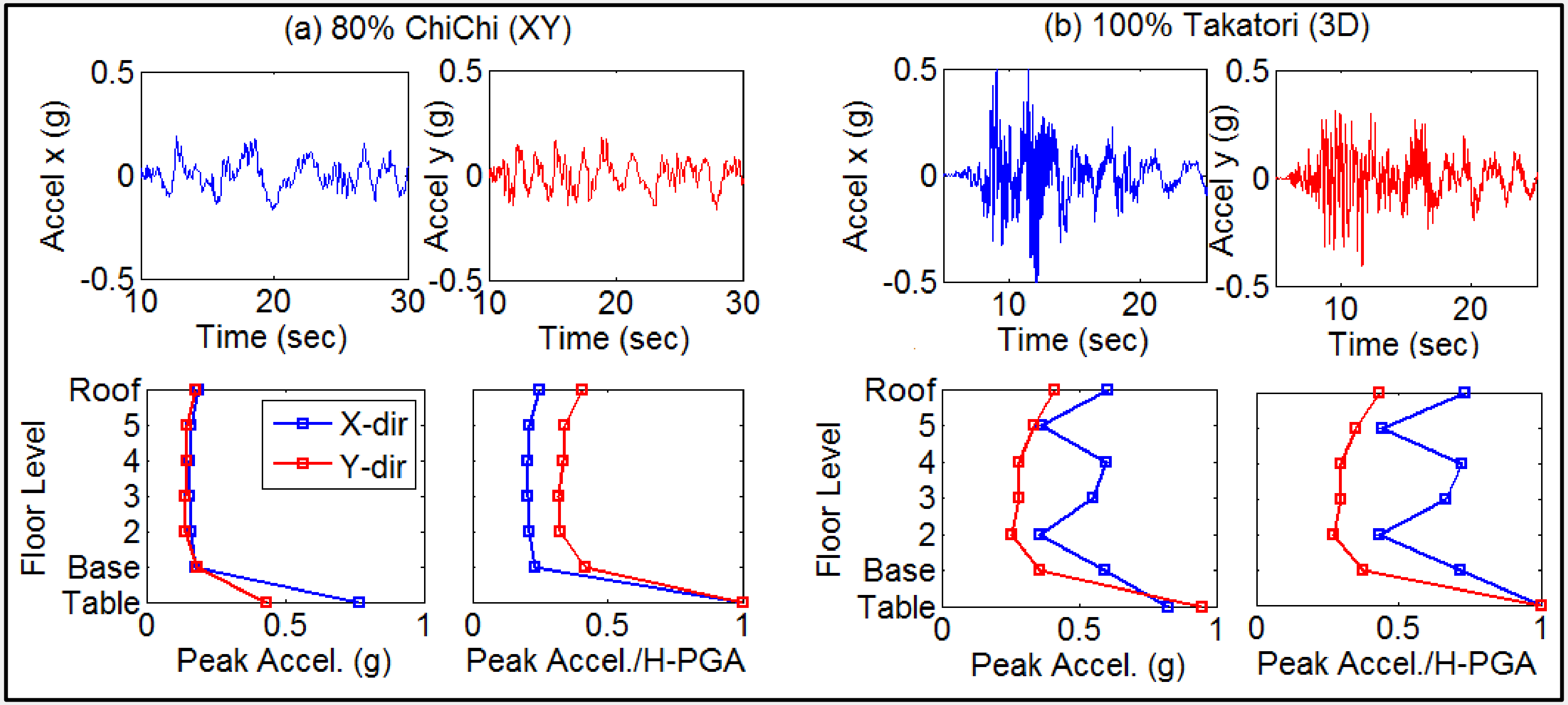
3rd Structural Mode
Y-direction
T = 0.1 sec



3rd Structural Mode
X-direction
T = 0.1 sec



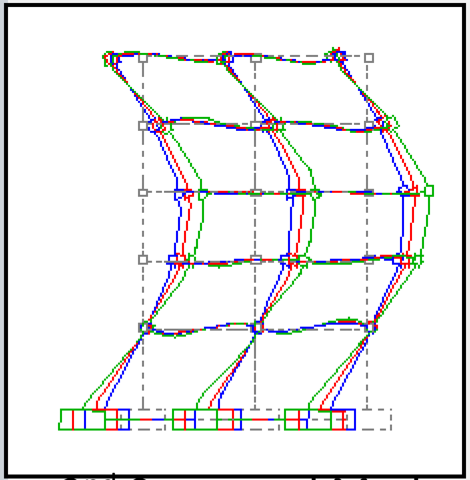
Floor Acceleration Response in TPB System, XY vs. 3D Motion



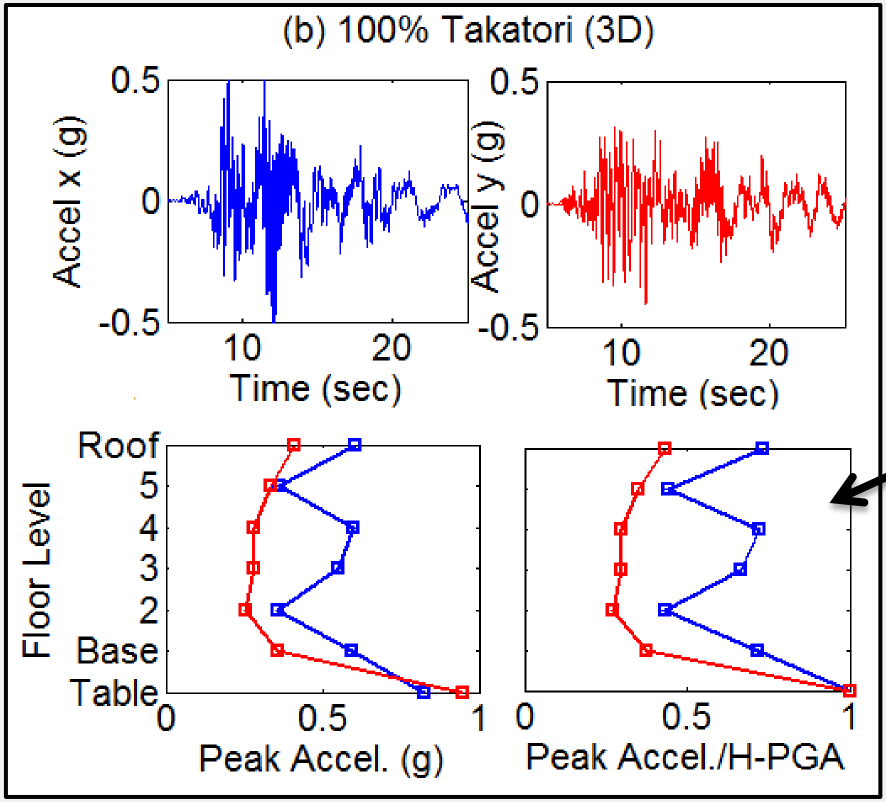
Ryan KL, Dao ND (2015). "Influence of vertical ground shaking on horizontal response of seismically-isolated buildings with friction bearings", *Journal of Structural Engineering (ASCE),* 142(1):0401531

Floor Acceleration Response in TPB System, 3D Takatori (Vert. PGA = 0.28g)

Mode 8



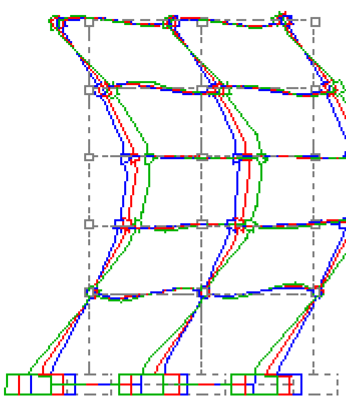
2nd Structural Mode
T = 0.17 sec



The acceleration profile in X-dir follows the 2nd structural mode.

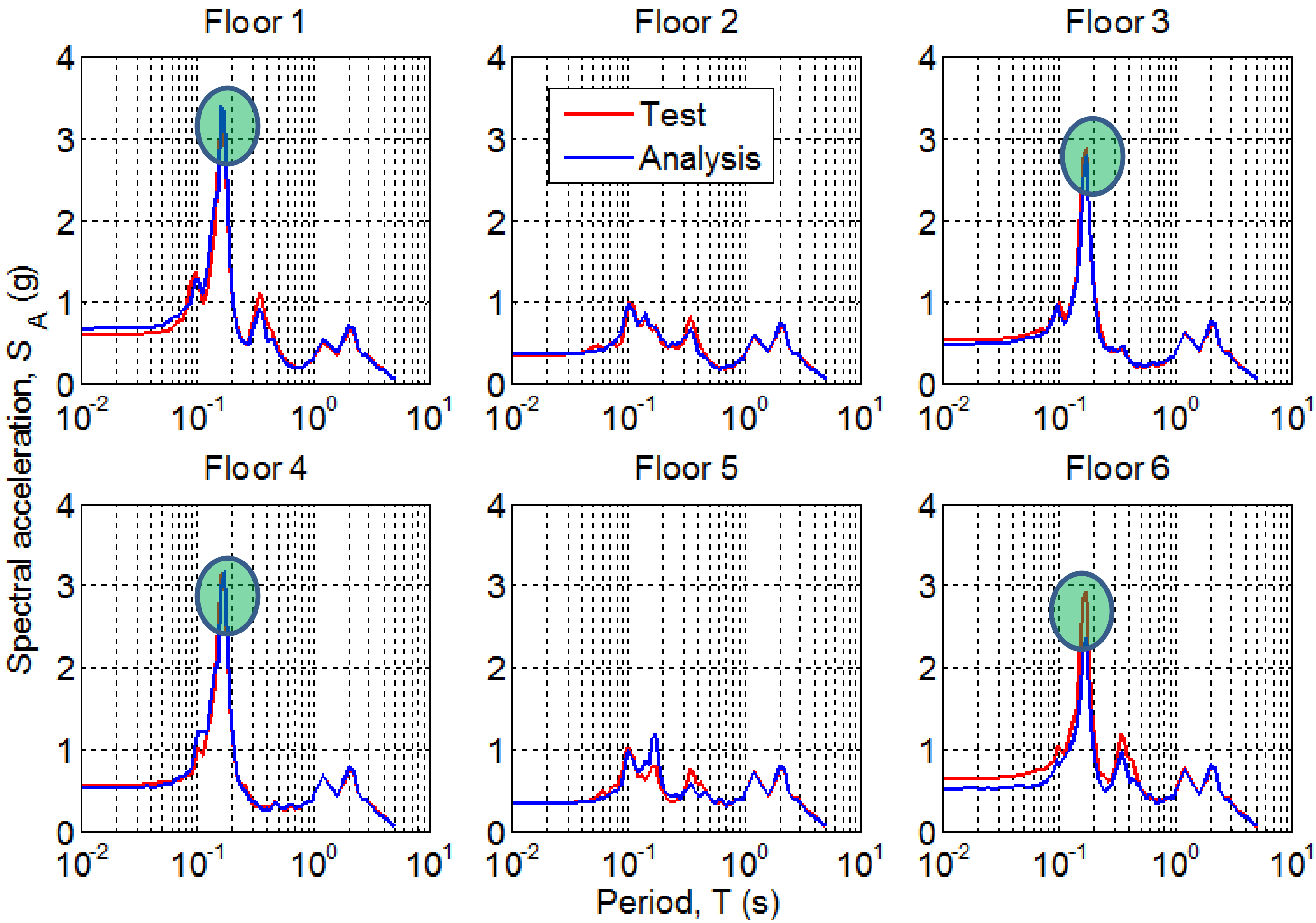
Analysis of Floor Spectra, TPB System 3D Input

Mode 8

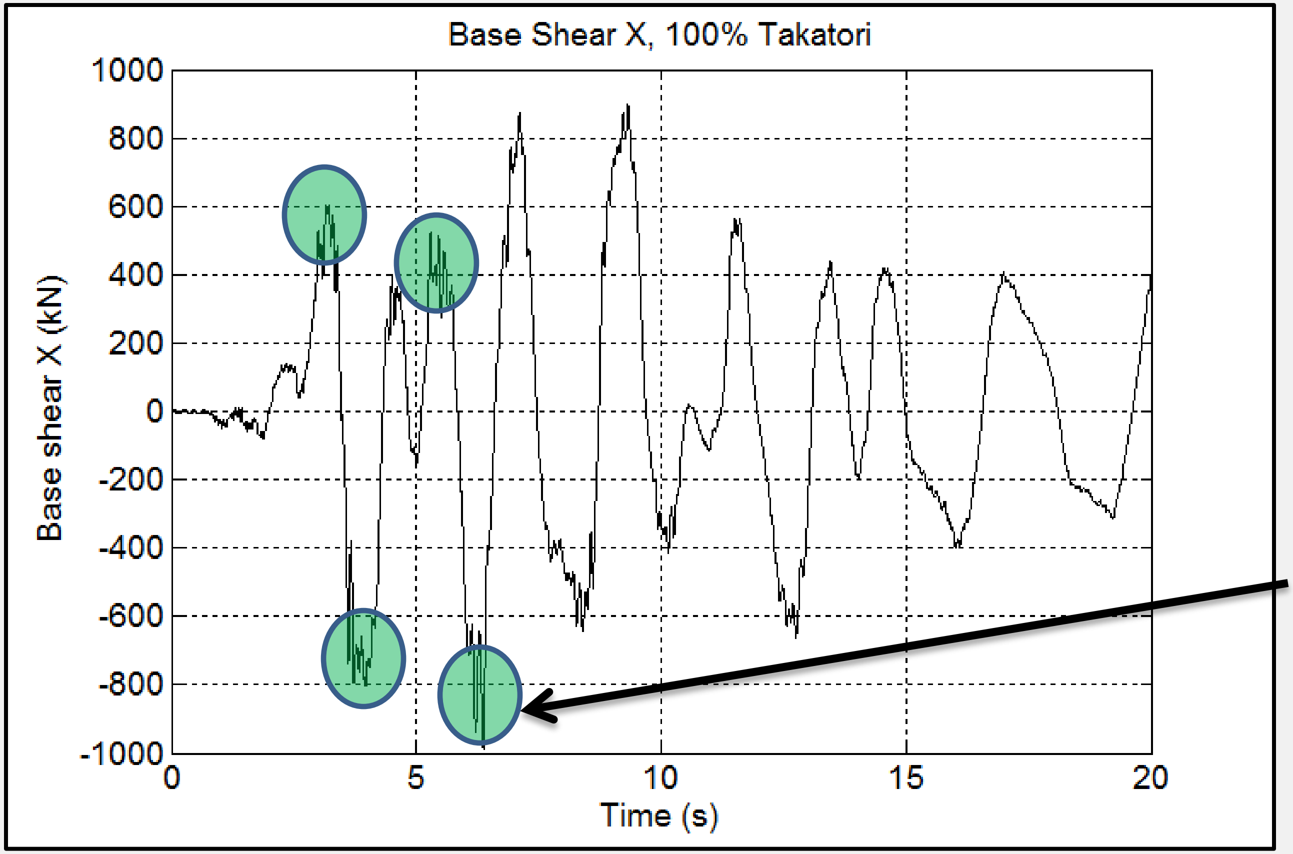


2nd Structural Mode
T = 0.17 sec

Floor Spectra for Takatori 100%, x-direction

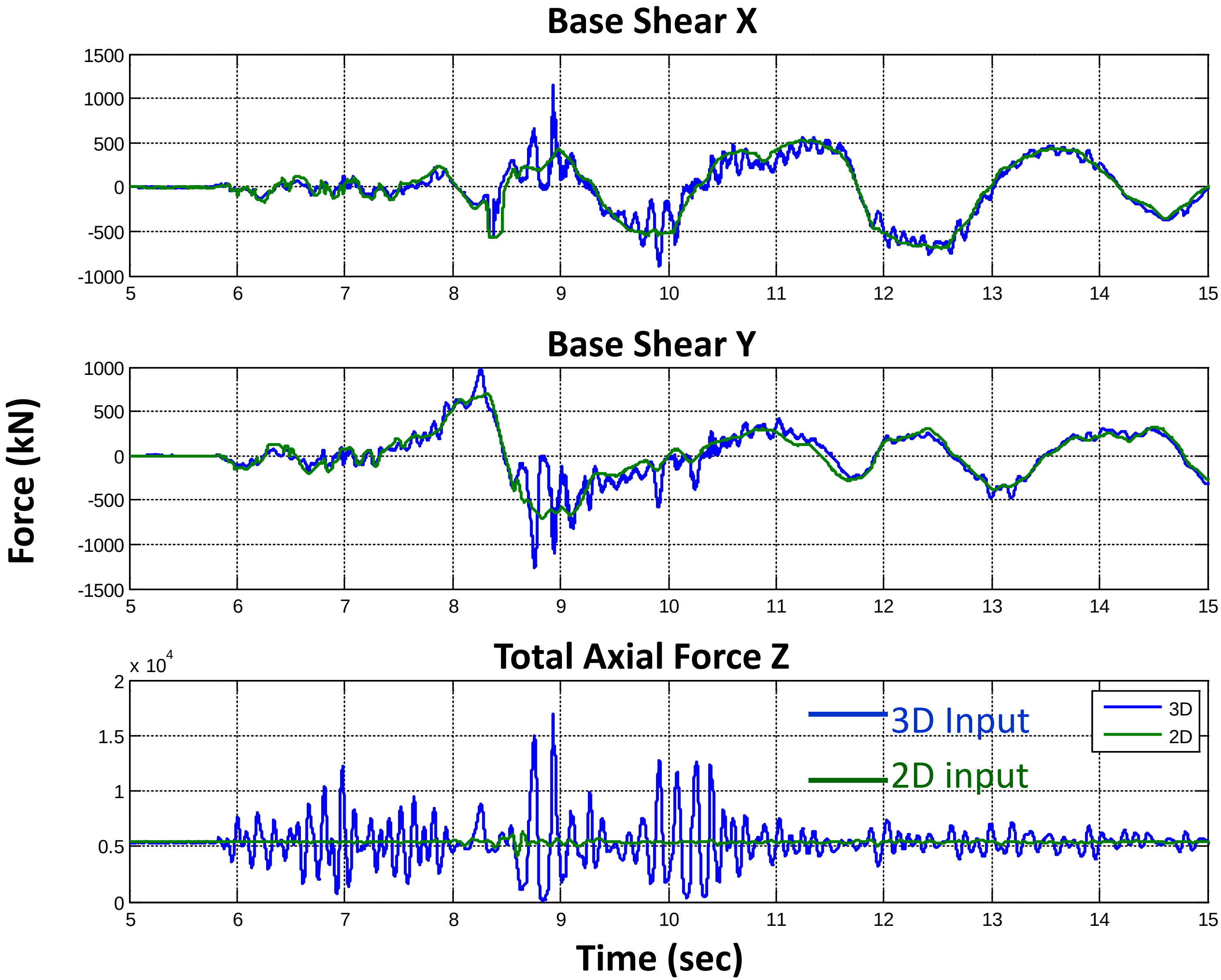


Base Shear in TPB System, 3D Takatori (Vert. PGA = 0.28g)



Oscillation at 7 Hz (0.14 sec) due to vertical acceleration is transmitted to the base shear, and amplifies the second structural mode.

Base Shear in 2D vs 3D Shaking TPB System, Northridge Rinaldi



Where do we go from here?

- ✓ Seismic isolation is still a pretty good system, but it is not the end all solution for everything.
- ✓ If design is driven by quantifiable performance requirements, the effects seen in the test can be predicted by analysis if the 3D input is considered
  - ✓ Acceleration amplification due to H-V coupling (3D input)
  - ✓ Vertical slab vibration (3D input)
- ✓ We have a long way to go to mitigate effects of vertical shaking, if this is found to be a worthwhile goal.

My Own Personal Discoveries

- ✓ **Always be prepared for the unexpected.**
- ✓ **Always remain objective.**
- ✓ **Understanding what happens in a test can take your very best detective skills, and can be a lot of fun.**
- ✓ **Important not to get too caught up in one test, and keep a balanced perspective of the big picture.**