nees@UCLA

The George E. Brown, Jr. Network for Earthquake Engineering Simulation

Earthquake and Structural Health Monitoring of Civil Structures

Bob Nigbor

NEES@UCLA

NEES = Network for Earthquake Engineering Simulation

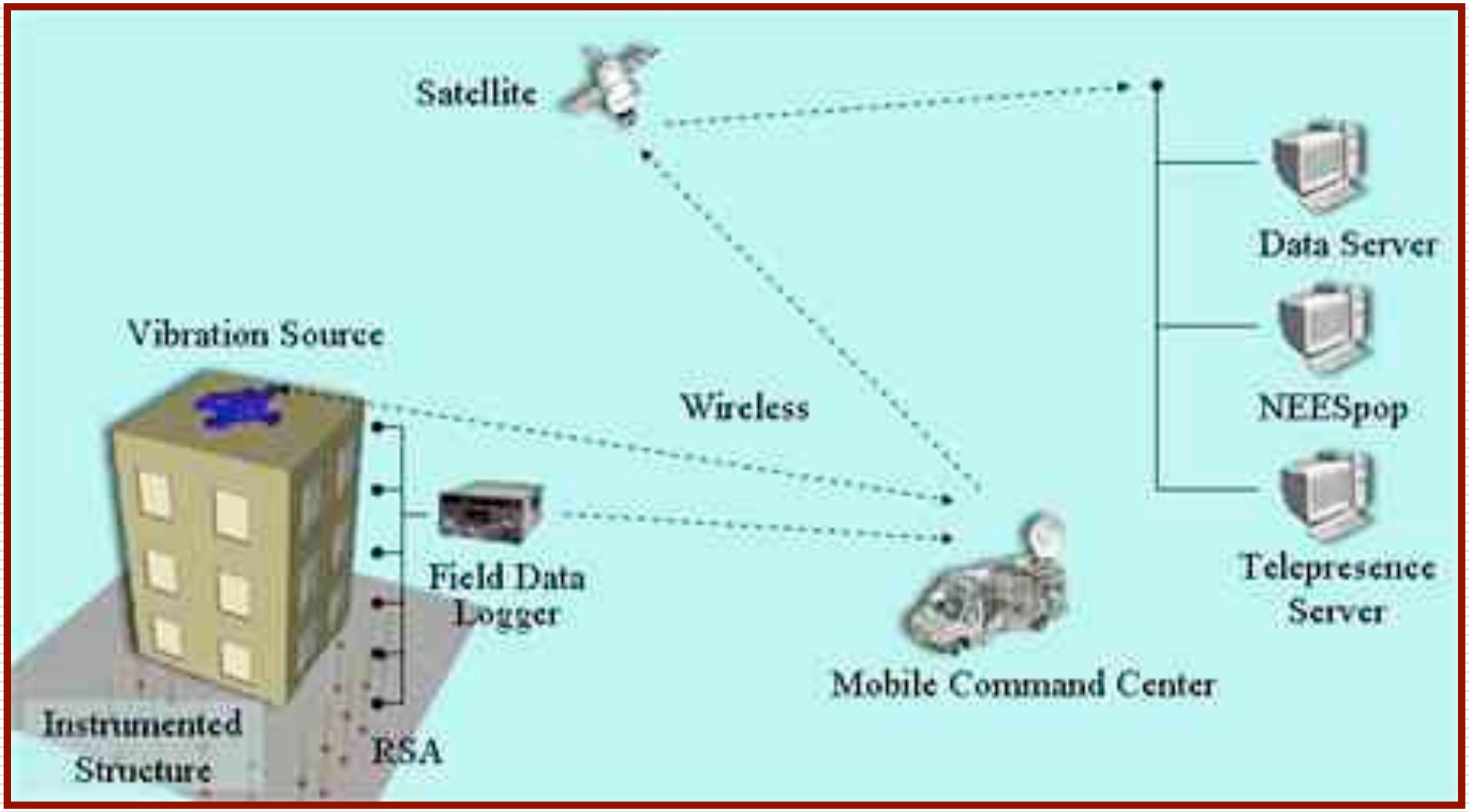
- Funded by National Science Foundation
- 5 year construction, 2000-2004
- 10-year operation, 2004-2015
- “Distributed Earthquake Engineering Laboratory”


Oregon State University
University of Colorado, Boulder
University of Minnesota
University of Illinois, Urbana-Champaign
University at Buffalo, SUNY
University of Nevada-Reno
Rensselaer Polytechnic University
University of California, Davis
Cornell University
University of California, Berkeley
Lehigh University
University of California, Los Angeles
University of California, San Diego
Brigham Young University
University of Texas at Austin

NEES Equipment Sites

- 4 Structures Labs
- 2 Centrifuges
- 3 Large Shake Table Labs
- 1 Geotechnical lifelines laboratory
- 1 Tsunami Wave Tank Lab
- 2 Mobile Field Labs (UCLA & UTA)
- 1 Permanent Field Site Facility

NEES@UCLA: Dynamic Field Testing of Civil Structures



Who is NEES@UCLA?

- Principal Investigators are:
  - John Wallace – Structural Engineering
  - Jon Stewart – Geotechnical Engineering
  - Robert Nigbor – Earthquake Engineering
- Professional Staff:
  - Steve Keowen – mechanical engineer
  - Alberto Salamanca – Instrumentation
  - Steve Kang – IT
  - Arlen Kam – Instrumentation
  - Erica Eskes - Administration

Vibration Sources

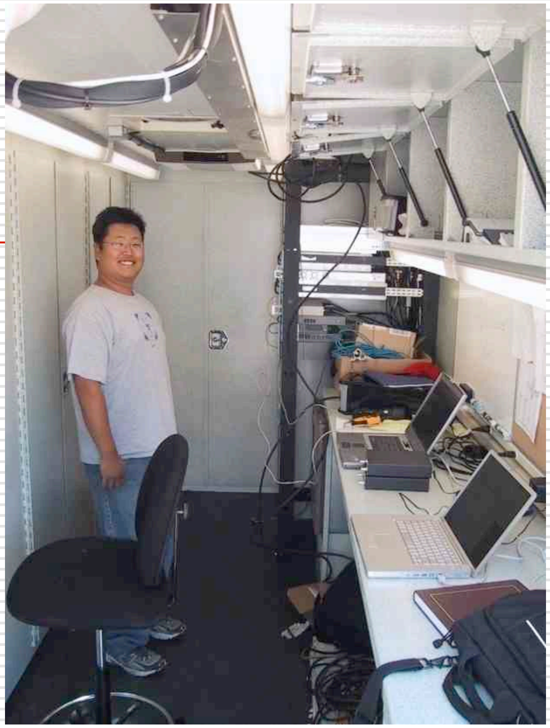
- **Eccentric mass shakers**
  - MK14A (1x)
    - omni-directional, 0 to 4.2 Hz & 15 kips
  - MK15 (2x)
    - uni-directional, 0 to 25 Hz & 100 kips
    - Synchronized – 200 kips
  - AFB
    - Uni-directional, 0 – 20 Hz & 10 kips
    - Fits in a pickup truck and elevator
- **Linear inertial shaker**
  - Digital controllers
  - 15 kips, ± 15 inches & 78 in/s

Data Acquisition and Sensors

- Kinemetrics
  - Q330 data loggers (120 channels total)
  - Episensor accelerometers
  - GPS time synchronization
  - Wireless telemetry using 802.11a/b
- National Instruments
  - SCXI/PXI combo chassis (>300 channels)
  - CompactRIO chassis
  - 16-24 bit resolution
  - GPS time synchronization
- Sensors
  - Strain gauges, load cells, displacement transducers, ++

High Performance Mobile Network

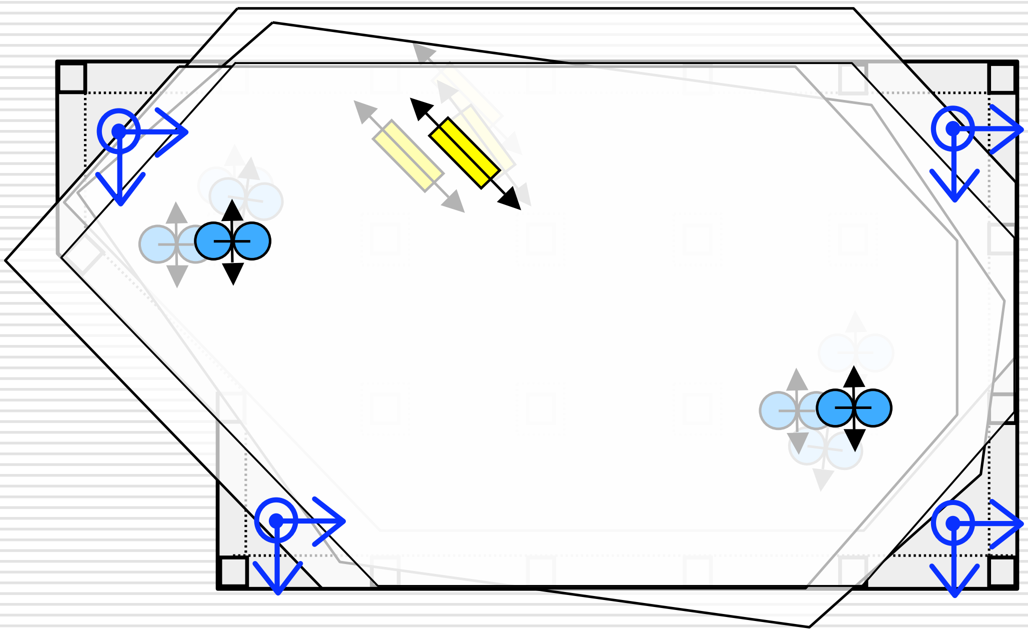
- **Mobile Command Center**
  - Satellite uplink
  - PC & UNIX workstations
- **Networking Equipment**
  - Wireless Field-LAN
  - Campus-LAN
  - Satellite transmission system



Example: Four Seasons Building Tests

- Forced-Vibration Testing
  - Sherman Oaks, California
  - 4-story RC Building (1977)
- Damaged (yellow tag) in Northridge earthquake
  - Empty, to be demolished
- Complete System Test
  - Shakers/Sensors & DAQ (200 sensor channels)
  - Mobile command center
  - Satellite, Tele-presence

Building Shaking Example: Four Seasons Building



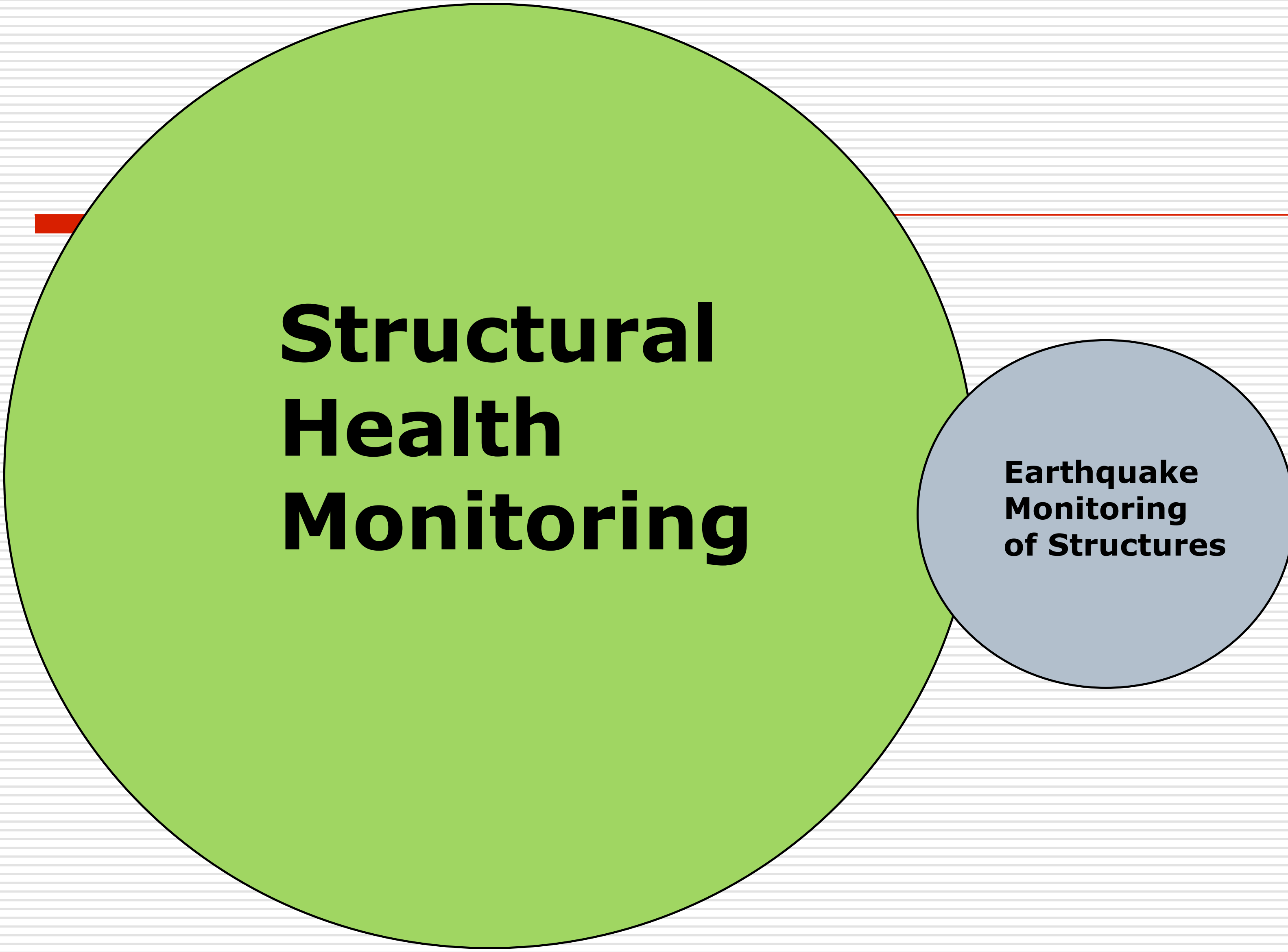
UCLA's large shakers:

100,000 lbs dynamic force each

Earthquake-Level Shaking (60%g peak)

Overview

- Earthquake Monitoring of Structures
- Structural Health Monitoring
- Examples:
  - Rama IX Bridge
  - UCLA Factor Building – Testbed for state-of-the-art monitoring
  - LAX Theme Building Testing and Monitoring


Structural
Health
Monitoring
Earthquake
Monitoring
of Structures

Who Monitors Structures for Earthquake Response in the U.S.?

CGS/CSMIP = California Geological Survey

USGS = U.S. Geological Survey

ANSS = Advanced National Seismic System

CENS = Center for Embedded Networked Systems

Nuclear Facilities

+ Other public & private

Why Monitor Structures?

The mission of response monitoring within ANSS is to provide data and information products that will (1) contribute to earthquake safety through improved understanding and predictive modeling of the earthquake response of engineered civil systems and (2) aid in post-earthquake response and recovery.

How?

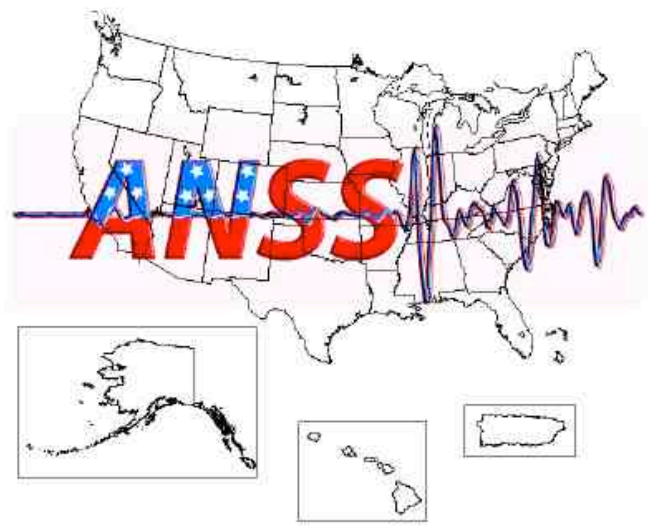
USGS
science for a changing world

GUIDELINE FOR ANSS SEISMIC MONITORING OF ENGINEERED CIVIL SYSTEMS—Version 1.0

Public Review Draft

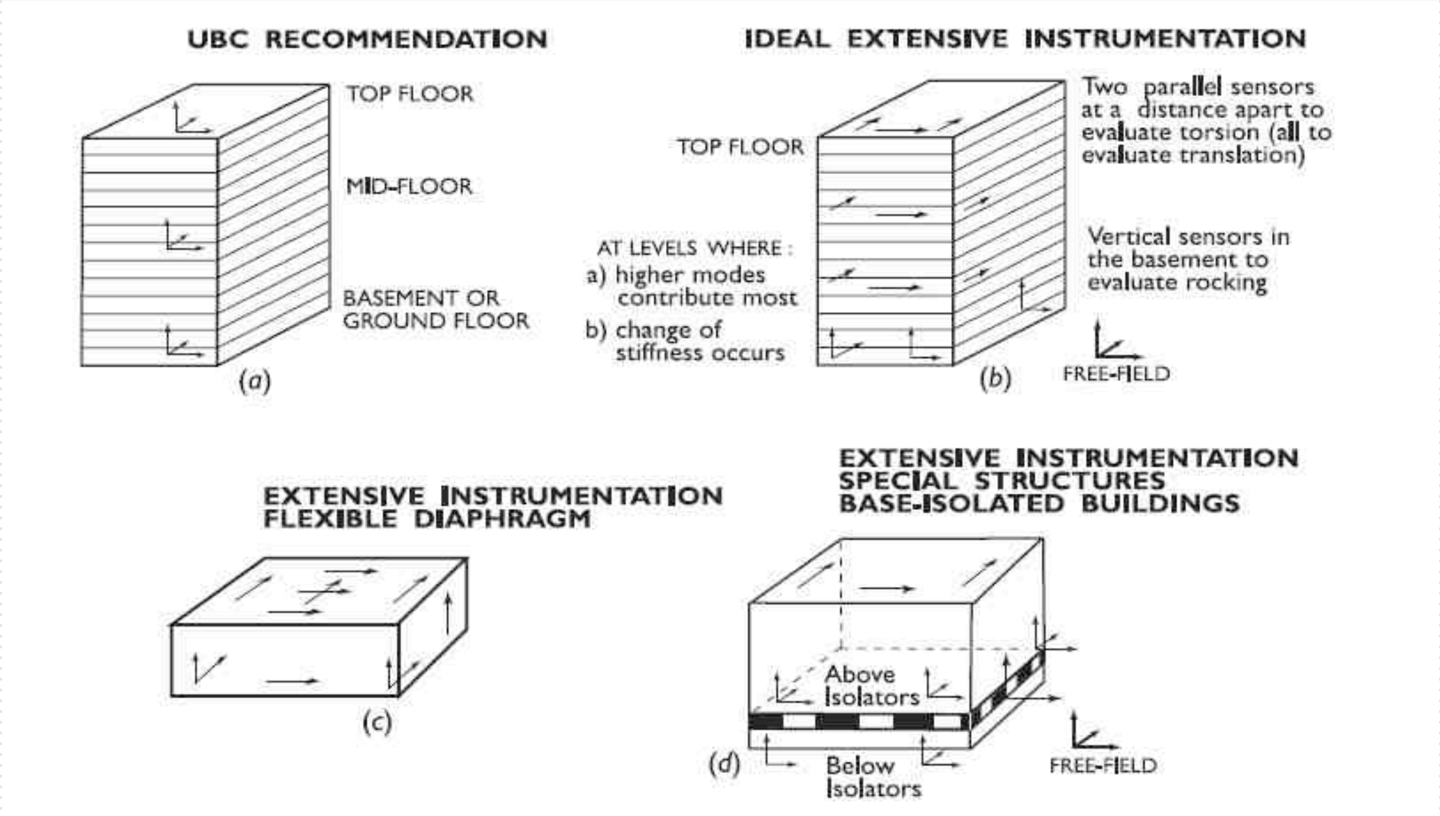
Prepared by the ANSS Structural Instrumentation Guideline Committee

Open-File Report 2005-1039, March 2005



U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Typical Building Instrumentation for Earthquakes



From Celebi, M., Current Practice and Guidelines for USGS Instrumentation of Buildings Including Federal Buildings , COSMOS Workshop on Structural Instrumentation, Emeryville, Ca. November 14-15, 2001

Sensors and Systems: Earthquake Monitoring

- Mostly accelerometers
- Some relative displacement sensors
- A few systems other sensor types (strain, GPS)

- Triggered central recording is most common
- Some continuous recording
- A few real-time monitoring systems

Frontier Building – Anchorage

Structure

- 14-story steel concrete moment frame
- Spread footings
- No basement
- Completed in 1981

Instrumentation

- 36 accelerometers
- Sensors on 8 levels
- Completed in 2007

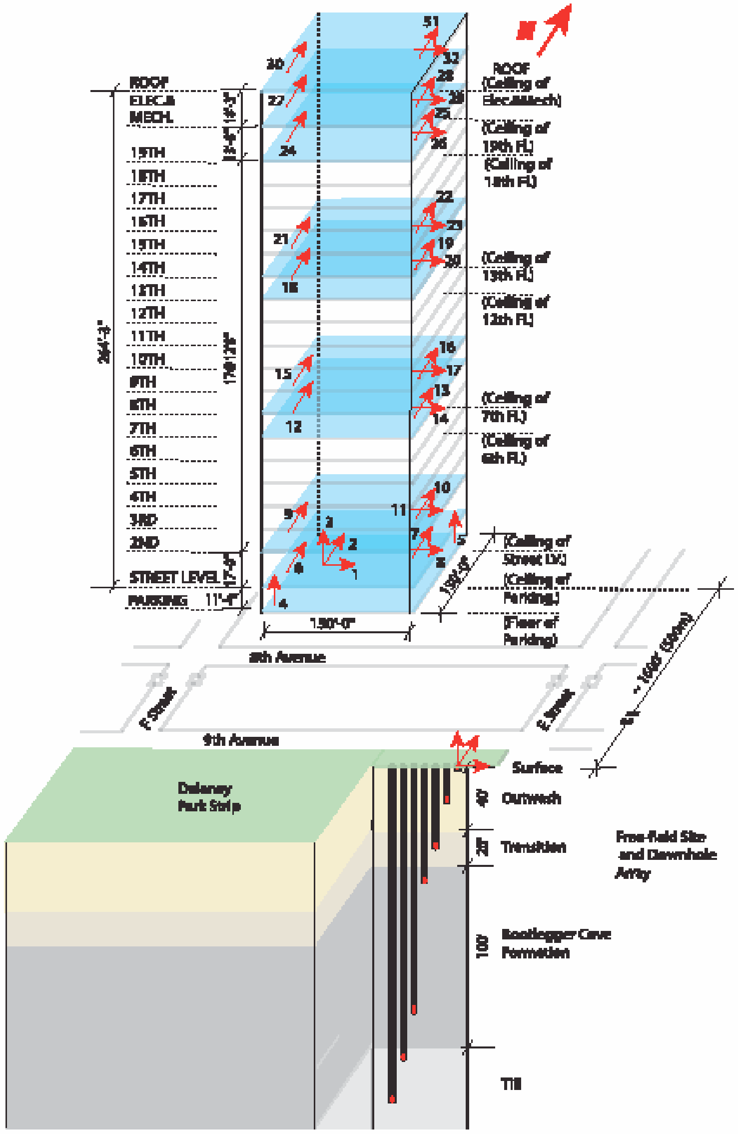
Atwood Building – Anchorage

Structure

- 20-story steel MRF
- RC Mat foundation
- One basement
- Completed in 1980

Instrumentation

- 32 accelerometers
- Sensors on 10 levels
- Nearby reference array
- Completed in 2003



Center for Engineering Strong Motion Data

CESMD - A Cooperative Effort

About CESMD

Data for Latest Earthquakes
Internet Quick Reports (IQR)

Archive

Search for Data
from Specific Stations or Structure Types

CISN | AEIC | PNSN | IMW | CEUS | NEIC | COSMOS

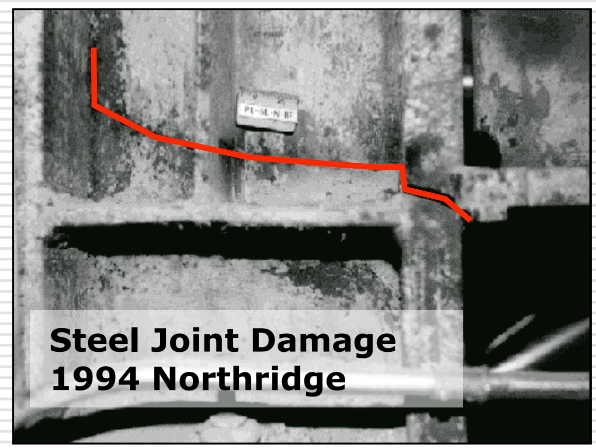
Partner Data Centers and Networks

Structural Health Monitoring (SHM)

- Assess health of instrumented structures from measurements
- Detect damage before reaching critical state and allow for rapid post-event assessment
  - – Potentially replacing expensive visual inspection which is impractical for wide spread damage in urban areas

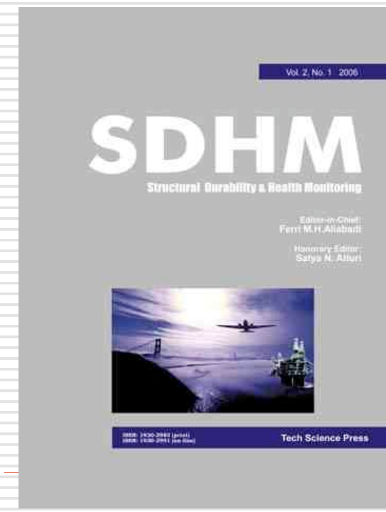

Arabdrill 19, UAE


I-35W Bridge 2007


Steel Joint Damage
1994 Northridge

The 7[th] International Workshop
Structural Health Monitoring – 2

SHM Journals



SHM Research

Pawel Malinowski, Tomasz Wandowski, Irina Trendafilova, and Wieslaw Ostachowicz
A Phased Array-based Method for Damage Detection and Localization in Thin Plates
Structural Health Monitoring 2009 8: 5-15. [Abstract] [PDF] [References] [Request Permission]

Upender K. Kaul
Modeling and Simulation of Normal and Damage Vibration Signatures of Idealized Gears
Structural Health Monitoring 2009 8: 17-28. [Abstract] [PDF] [References] [Request Permission]

Tribikram Kundu, Samik Das, and Kumar V. Jata
Health Monitoring of a Thermal Protection System using Lamb Waves
Structural Health Monitoring 2009 8: 29-45. [Abstract] [PDF] [References] [Request Permission]

A.J. Cardini and J.T. DeWolf
Long-term Structural Health Monitoring of a Multi-girder Steel Composite Bridge Using Strain Data
Structural Health Monitoring 2009 8: 47-58. [Abstract] [PDF] [References] [Request Permission]

Vassilios Kappatos and Evangelos Dermatas
Feature Selection for Robust Classification of Crack and Drop Signals
Structural Health Monitoring 2009 8: 59-70. [Abstract] [PDF] [References] [Request Permission]

Seunghee Park, Gyuhae Park, Chung-Bang Yun, and Charles R. Farrar
Sensor Self-diagnosis Using a Modified Impedance Model for Active Sensing-based Structural Health Monitoring
Structural Health Monitoring 2009 8: 71-82. [Abstract] [PDF] [References] [Request Permission]

P. Naga Srinivasa Rao and V.N. Achutha Naikan
An Algorithm for Simultaneous Optimization of Parameters of Condition-based Preventive Maintenance
Structural Health Monitoring 2009 8: 83-94. [Abstract] [PDF] [References] [Request Permission]

Fundamental Axioms of SHM

(Worden, Farrar, Manson & Park, 2007)

Axiom I: All materials have inherent flaws or defects;

Axiom II: The assessment of damage requires a comparison between two system states;

Axiom III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode;

Axiom IVa: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information;

Axiom IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions;

Fundamental Axioms of SHM

(Worden, Farrar, Manson & Park, 2007)

Axiom V: The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system;

Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability;

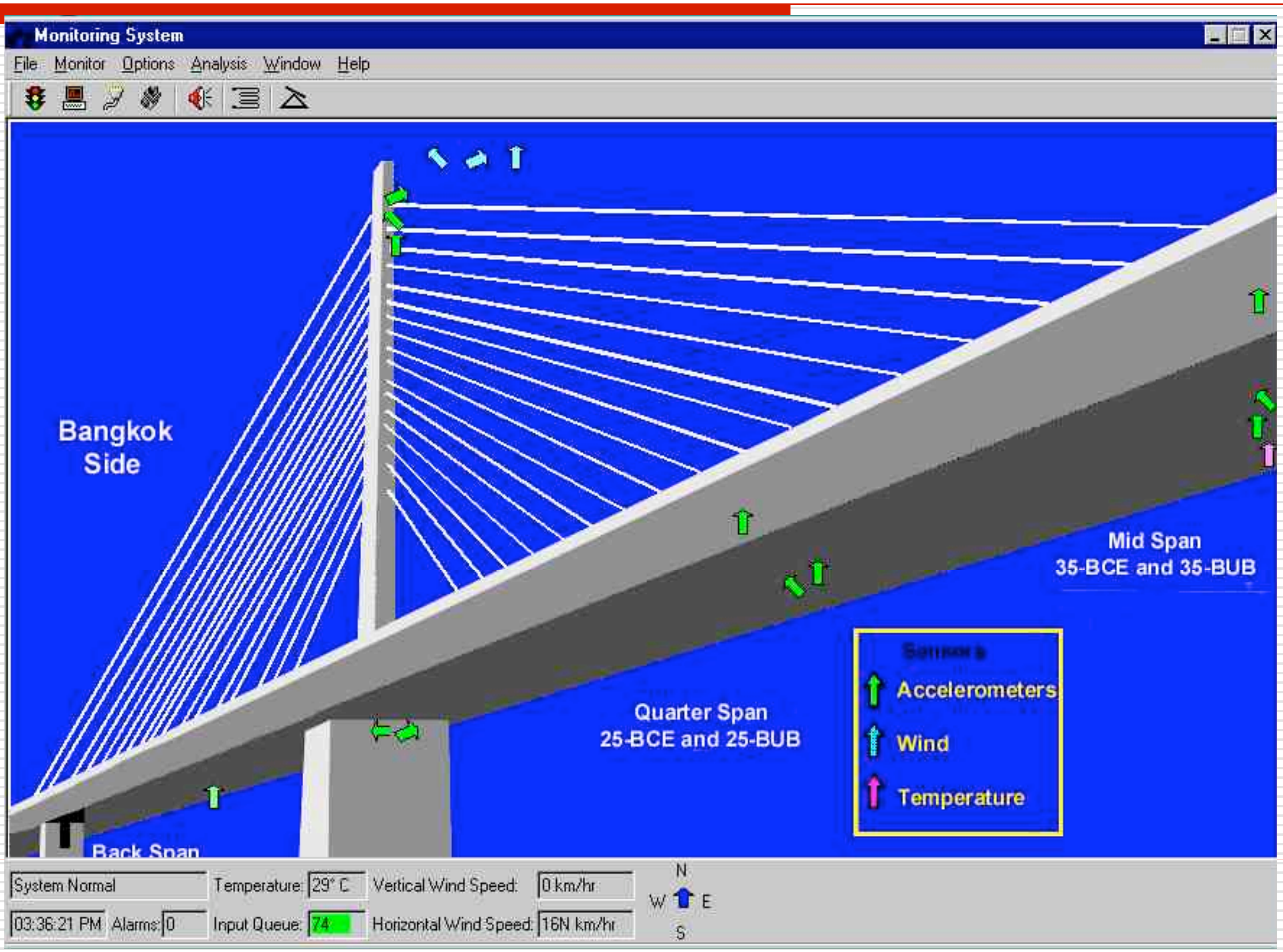
Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

Sensors and Systems: SHM of Civil Structures

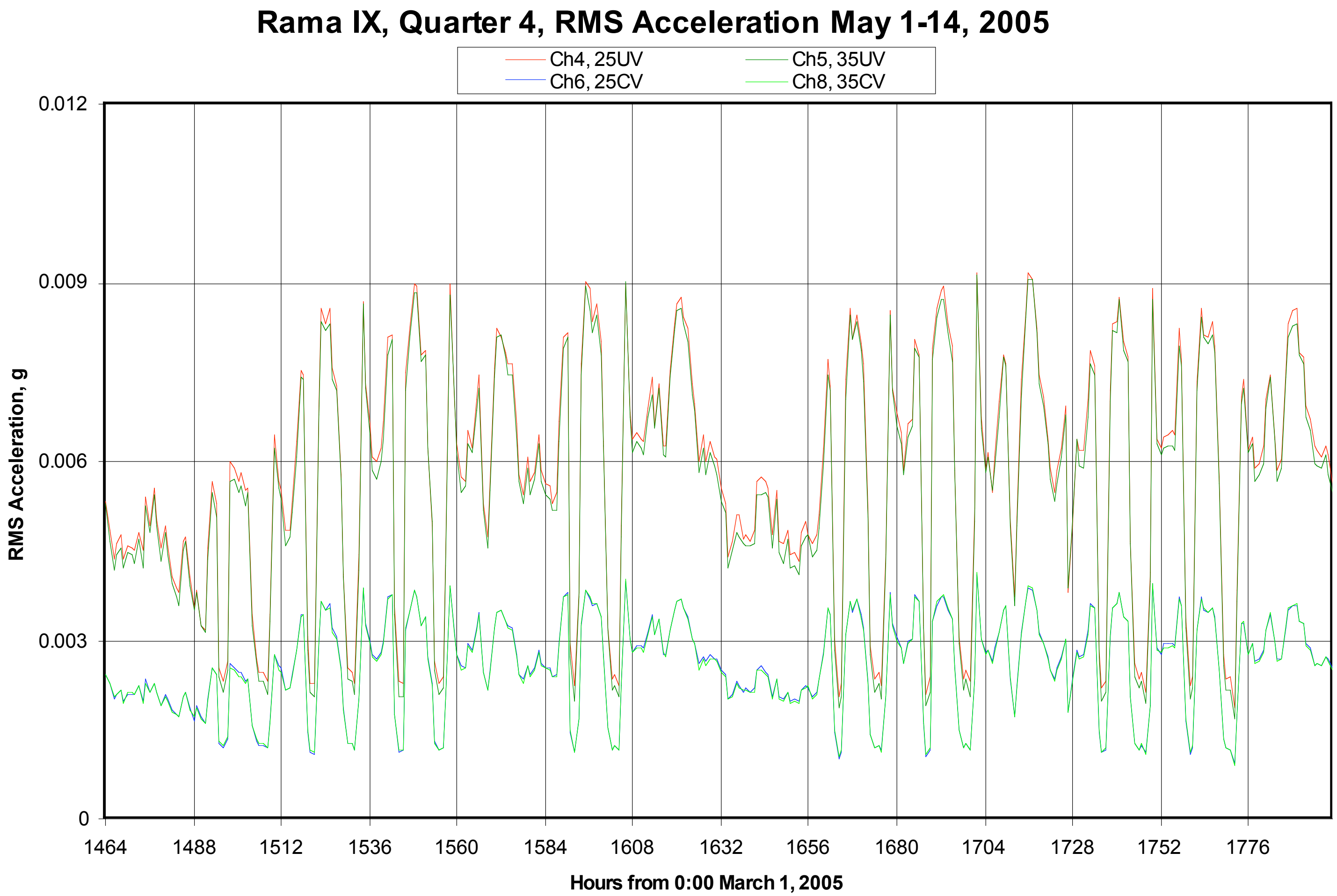
- For vibration-based monitoring, accelerometers & strain & displacement
- For static monitoring, displacement, tilt, strain, corrosion, force, +++
- Embedded sensors in concrete & steel components to make “smart materials”

- Continuous recording the norm
- Real-time processing & analysis common

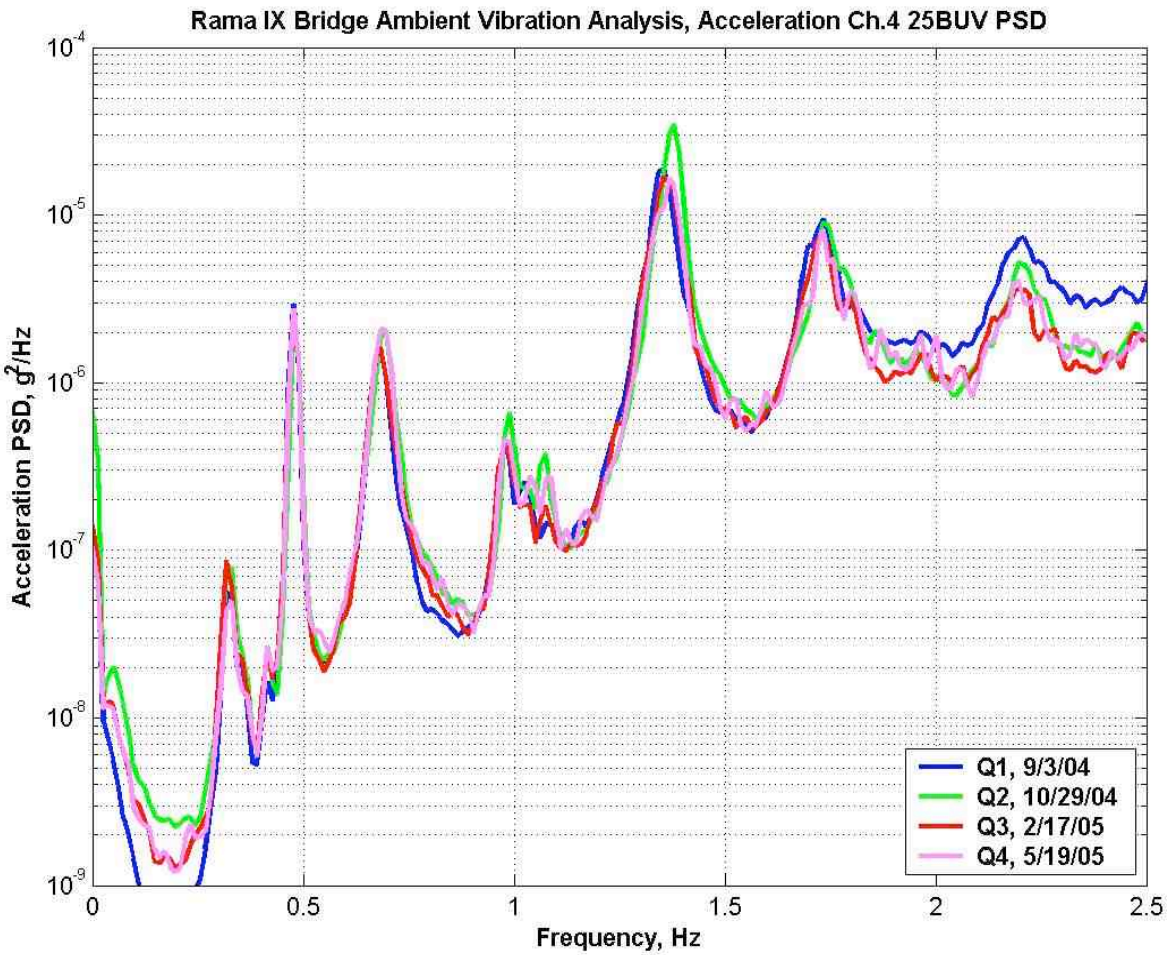
Example: SHM of Rama IX Bridge in Bangkok



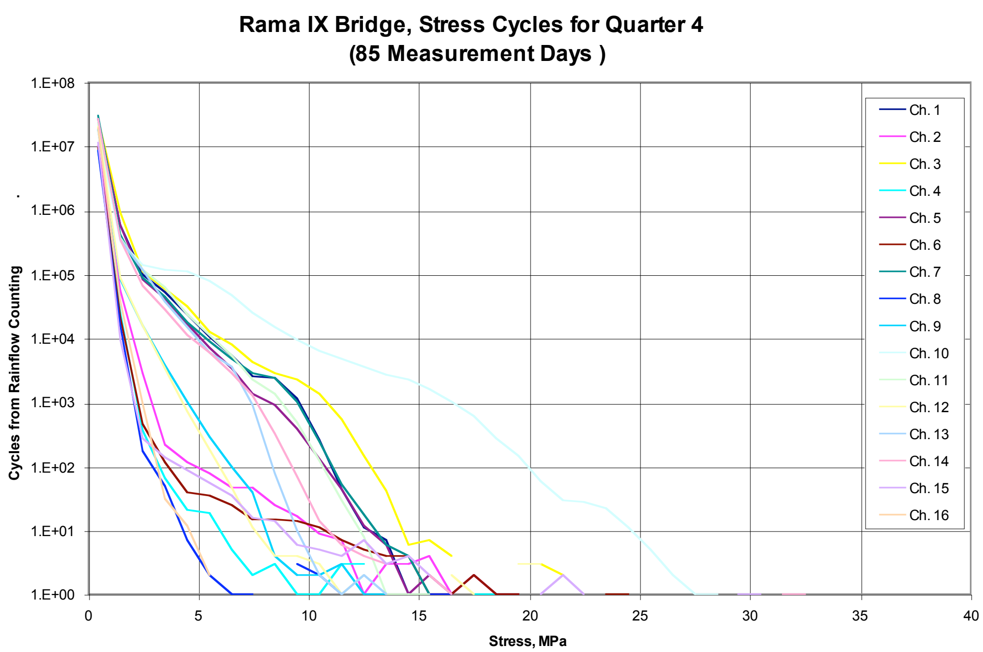
Acceleration Statistics

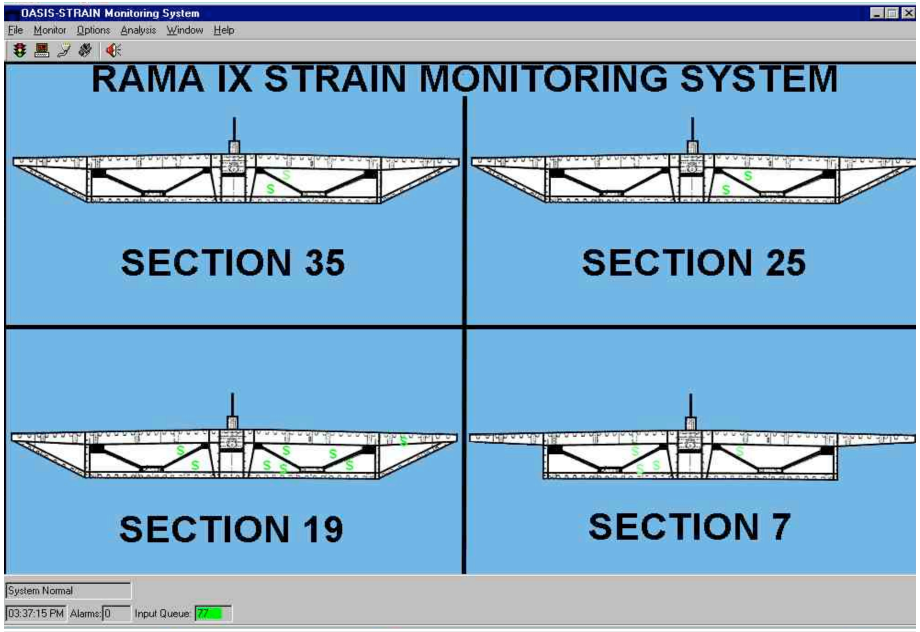


Vibration-Based Monitoring

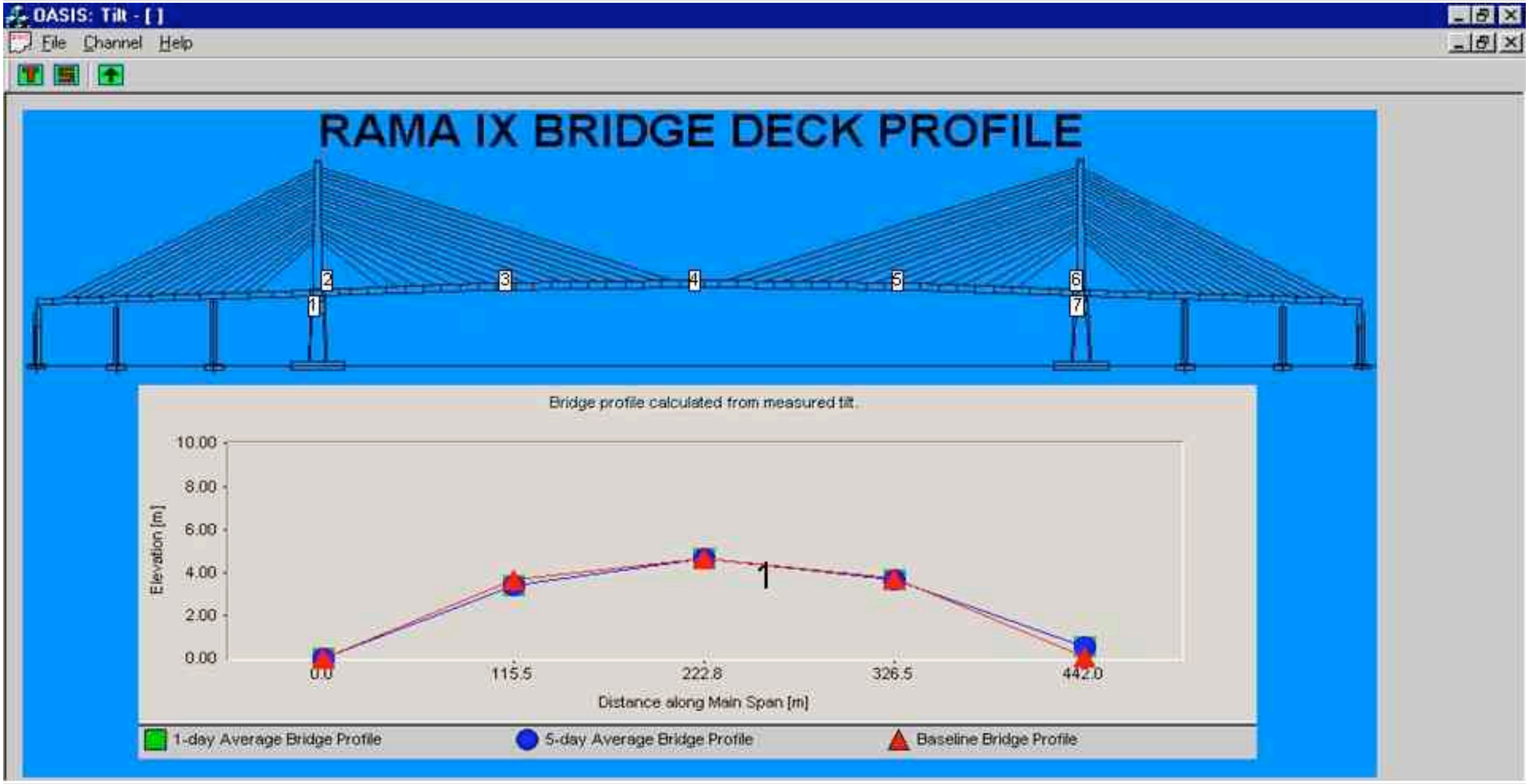


Strain & Fatigue Monitoring



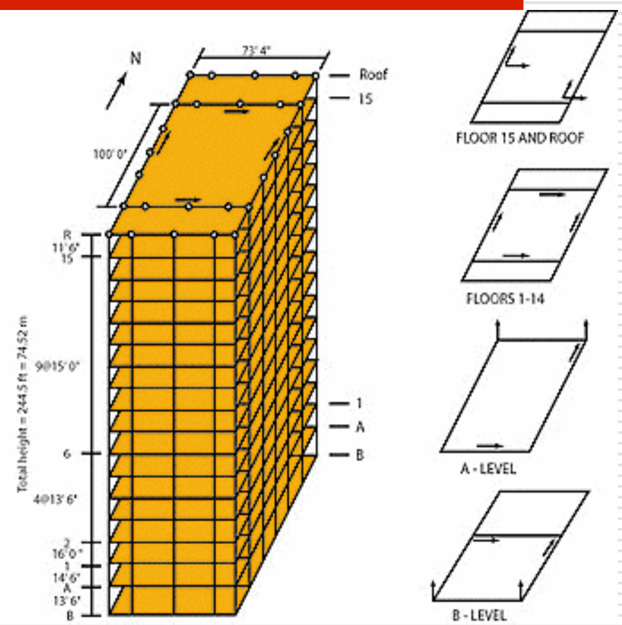


Long-Term Tilt & Profile Monitoring



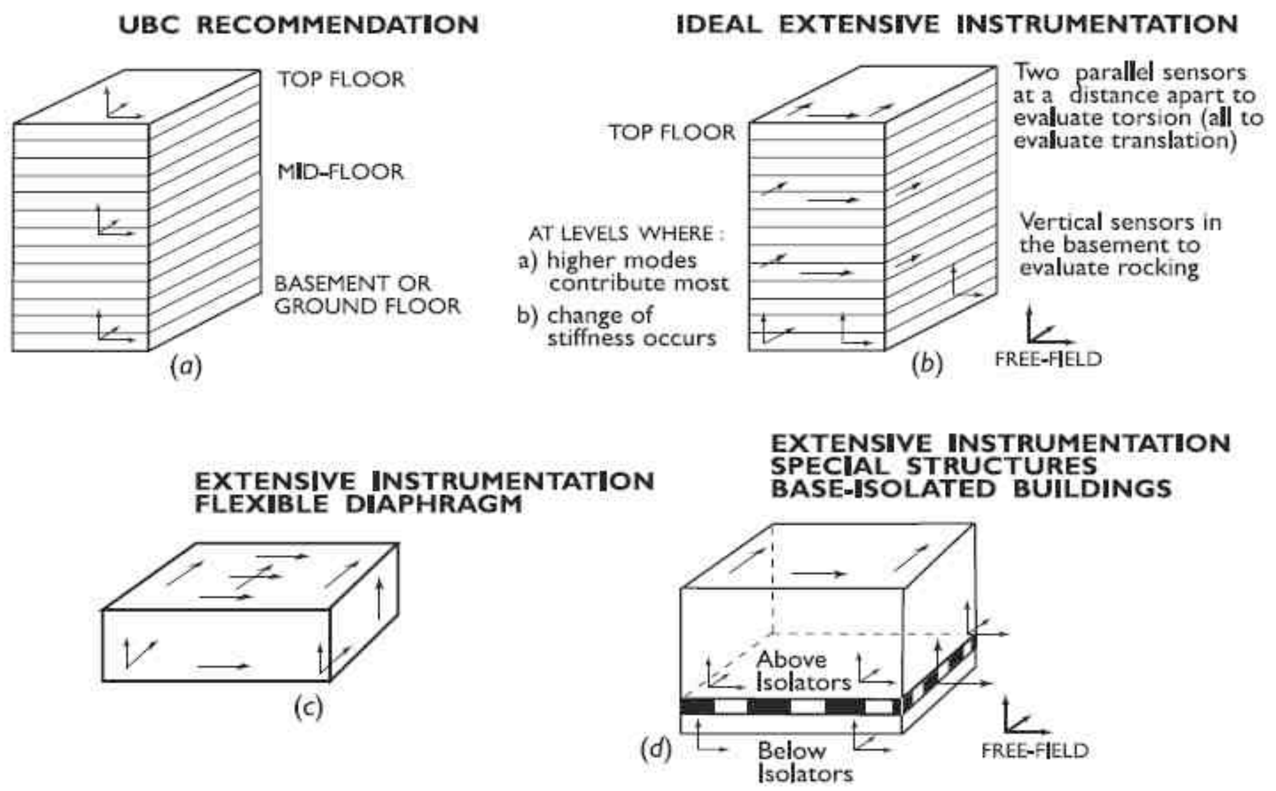
UCLA Factor Building

Instrumented by CENS and USGS/ANSS



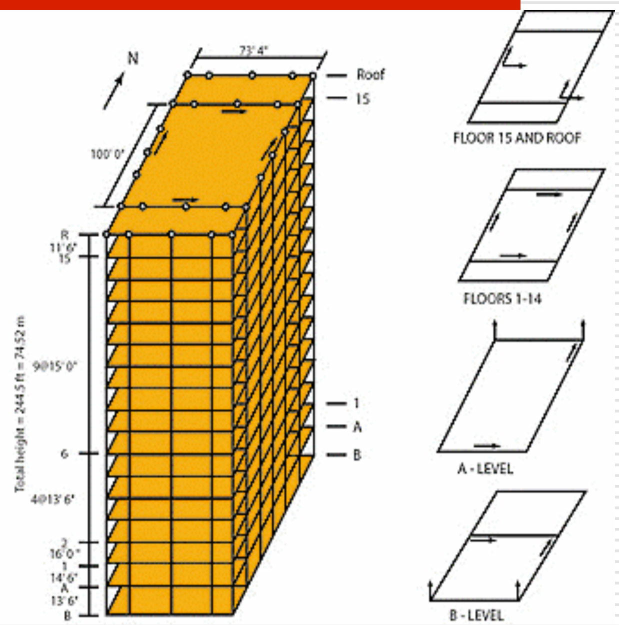
- On UCLA Campus
- 17-story steel-frame construction
- **72 channels of acceleration, 4 per floor**
- **Continuous, real-time 24-bit data acquisition**
- 500sps initially, now 100sps
- Data are open - available through ANSS

Typical Building Instrumentation for Earthquakes is SPARSE



From Celebi, M., Current Practice and Guidelines for USGS Instrumentation of Buildings Including Federal Buildings , COSMOS Workshop on Structural Instrumentation, Emeryville, Ca. November 14-15, 2001

Factor Building instrumentation is **DENSE** and **COMPLETE**



- On UCLA Campus
- 17-story steel-frame construction
- **72 channels of acceleration, 4 per floor**
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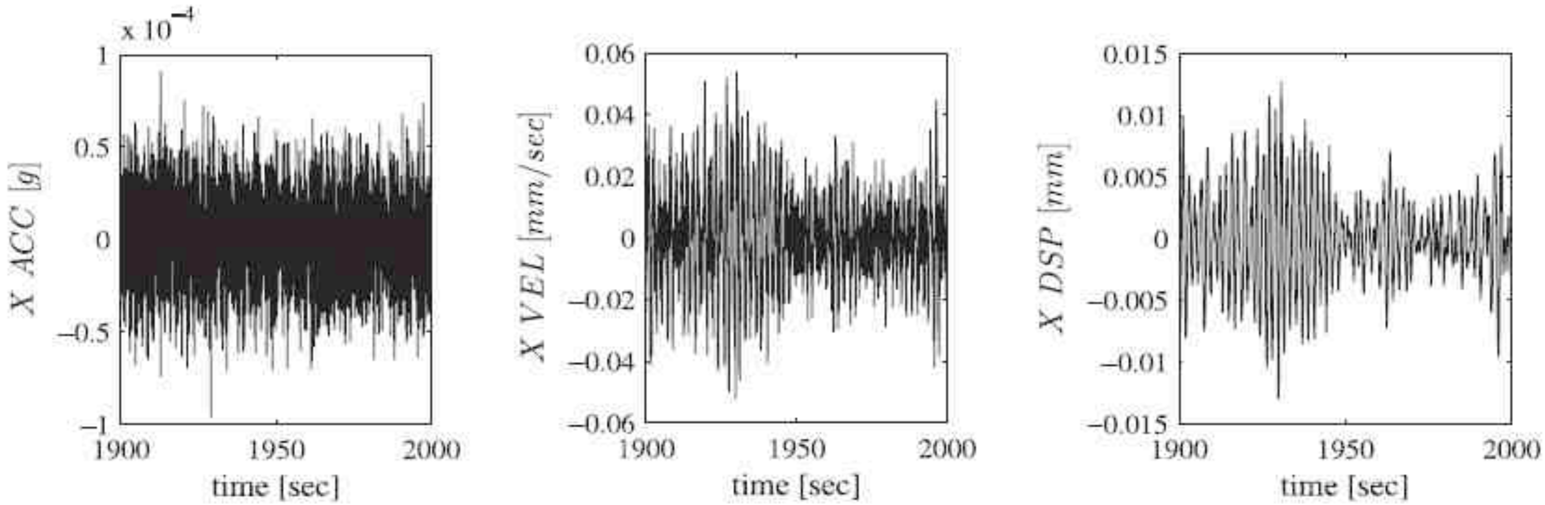
- 500sps initially, now 100sps
- Data are open - available through ANSS

Factor Building – Testbed for Monitoring & Analysis Methods

1. Kohler, Davis & Safak – Conventional FFT-based analysis & mode shape animation for ambient and small EQ
2. Skolnik, Lei, Yu, & Wallace – FEM model updating using identified modal properties
3. Nayeri, Masri, Ghanem & Nigbor – Variability of modal parameters, new method for linear & nonlinear story stiffness estimation.
4. Nigbor, Hansen, Tileylioglu, & Baek – Use of elevators as repeatable excitation for health monitoring

Sample Factor Ambient Vibration

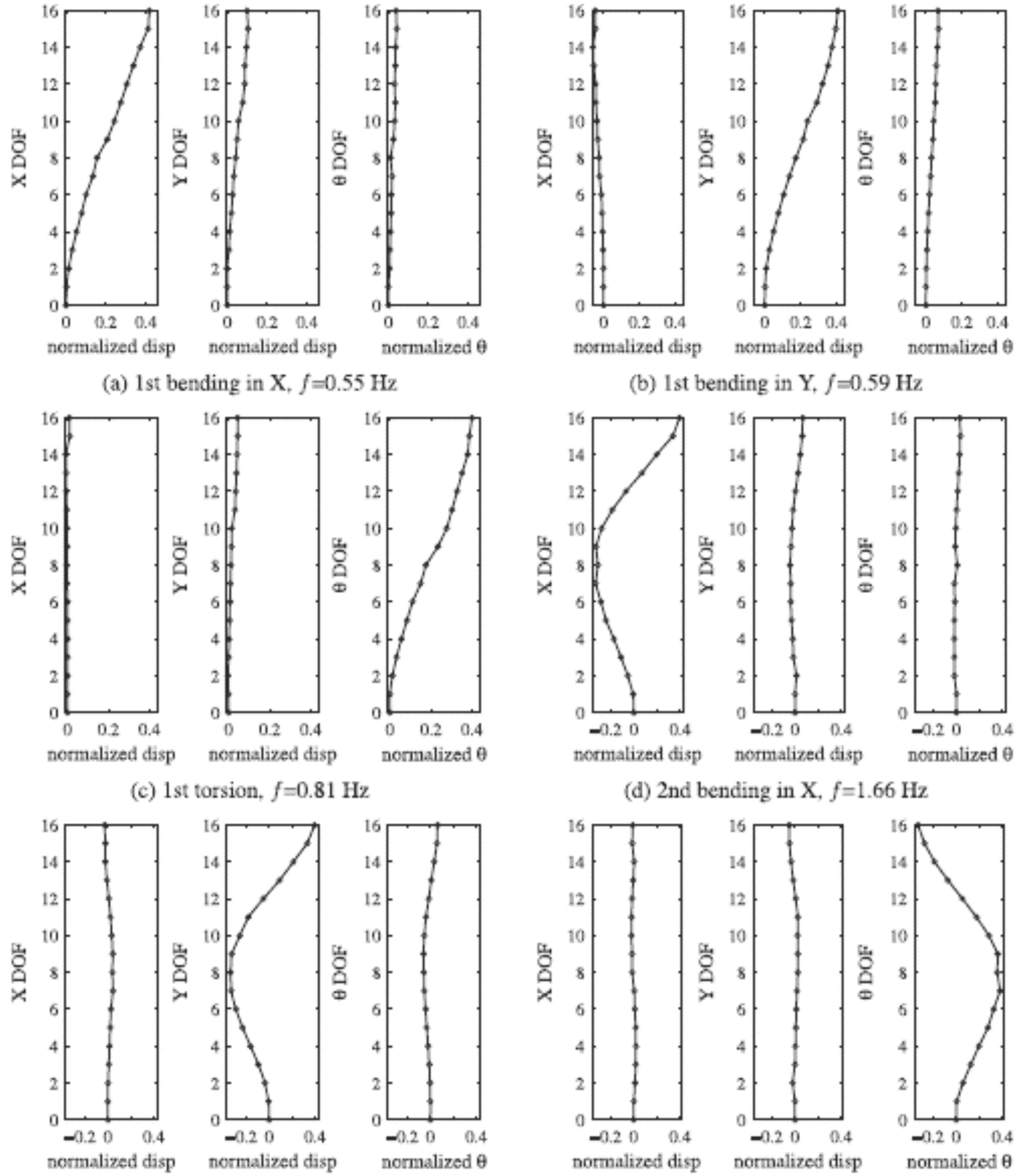


(a) Acceleration (b) Velocity (c) Displacement

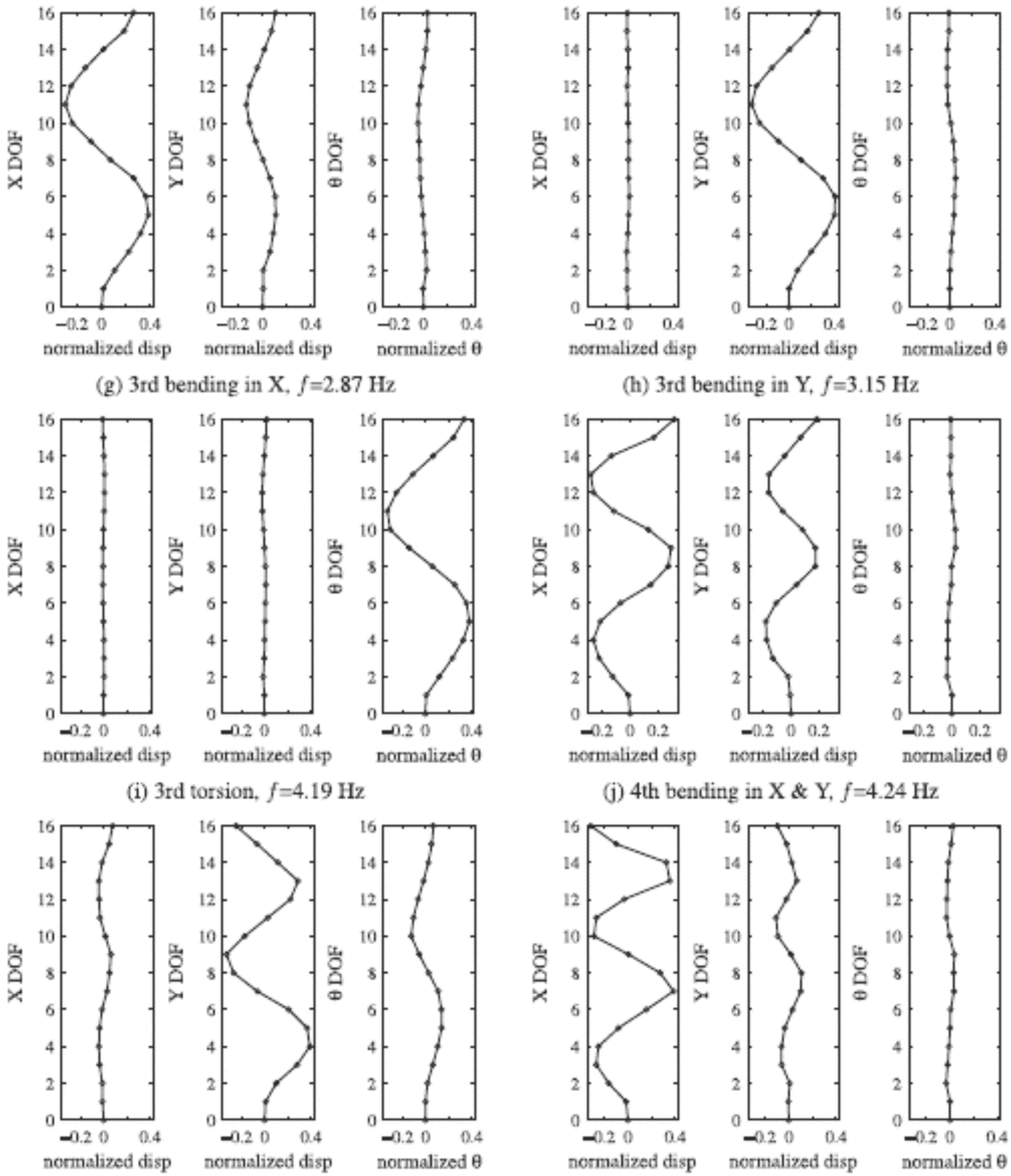
Figure 4. A typical ambient vibration record of the acceleration time-history measured at the 14th floor of the Factor building in the E–W direction, and its corresponding velocity and displacement time-histories computed by digital signal processing. (a) Measured acceleration; (b) processed velocity, and (c) processed displacement.

<milli-g acceleration, 10s of micron displacements

Identified Mode Shapes, Conventional Spectrum Analysis



Identified Mode Shapes, Conventional Spectrum Analysis



(g) 3rd bending in X, f=2.87 Hz

(h) 3rd bending in Y, f=3.15 Hz

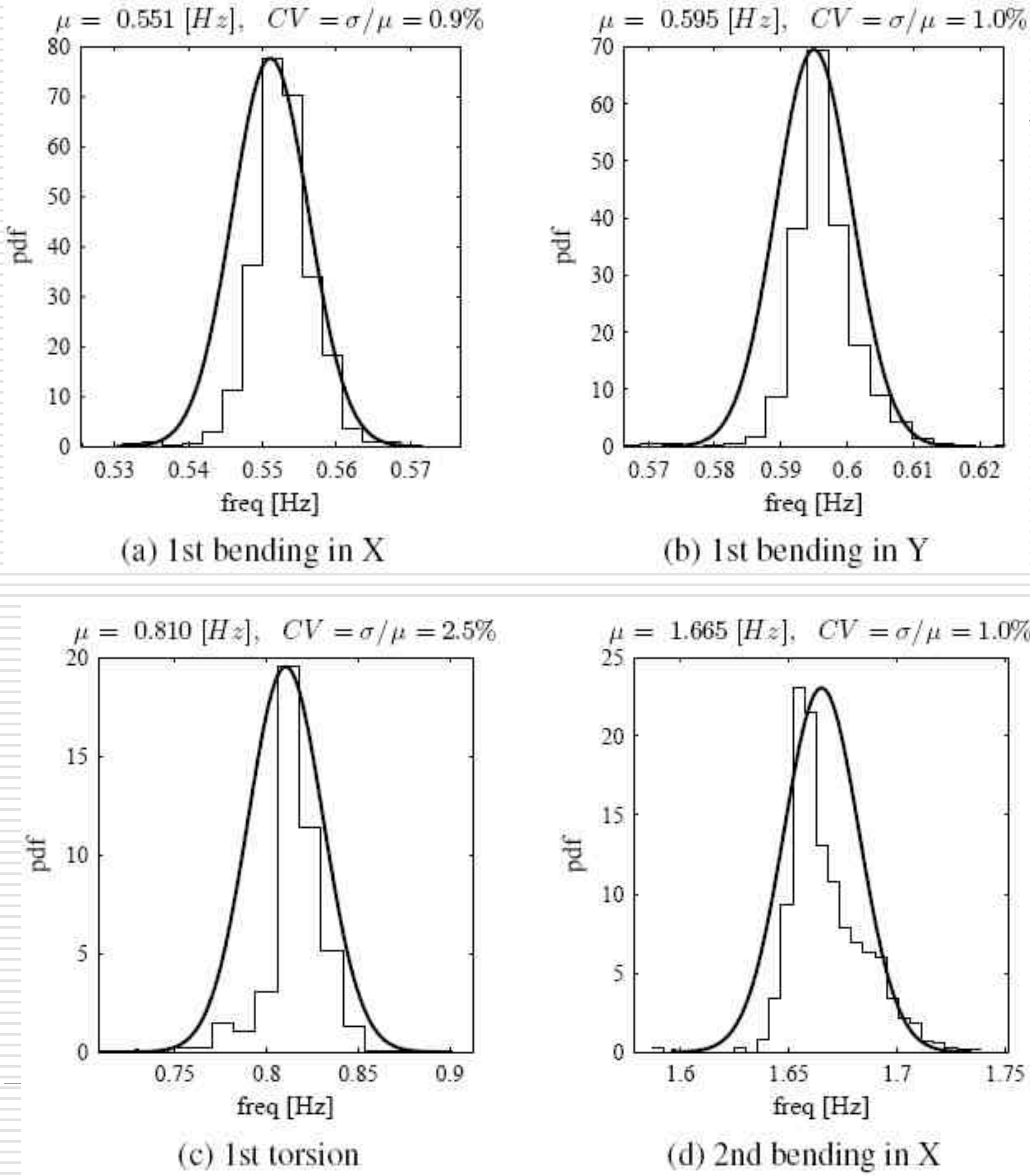
(i) 3rd torsion, f=4.19 Hz

(j) 4th bending in X & Y, f=4.24 Hz

(k) 4th bending in Y, f=4.51 Hz

(l) 5th bending in X, f=5.21 Hz

Uncertainty Quantification of the Modal Parameters



(a) 1st bending in X

(b) 1st bending in Y

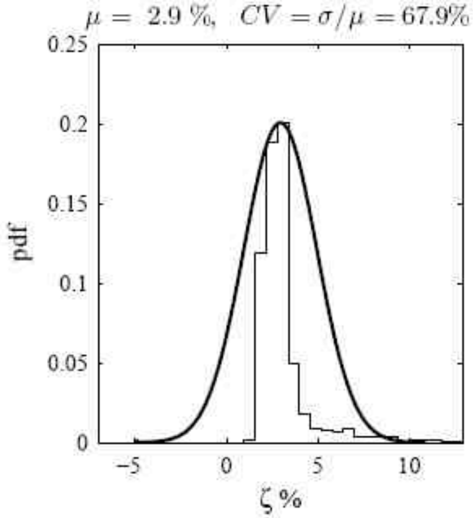
(c) 1st torsion

(d) 2nd bending in X

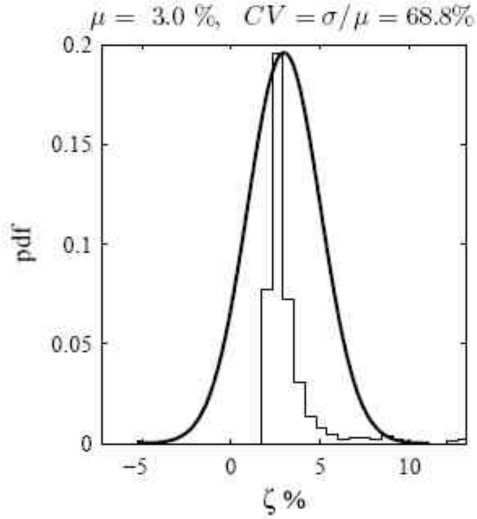
distribution of the estimated modal frequencies for the Factor Building.

A total of 50 days of data (each 24 hours) were considered in this study. The modal parameter identification was conducted over time-windows of 2 hours each, and with 50% overlap, for a total number of 1200 statistical ensembles.

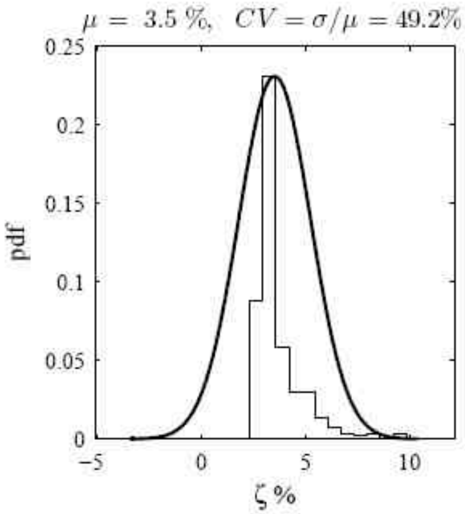
Uncertainty Quantification of the Modal Parameters



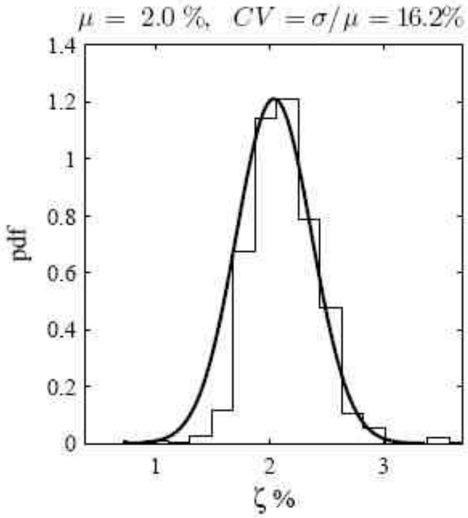
(a) 1st bending in X



(b) 1st bending in Y



(c) 1st torsion

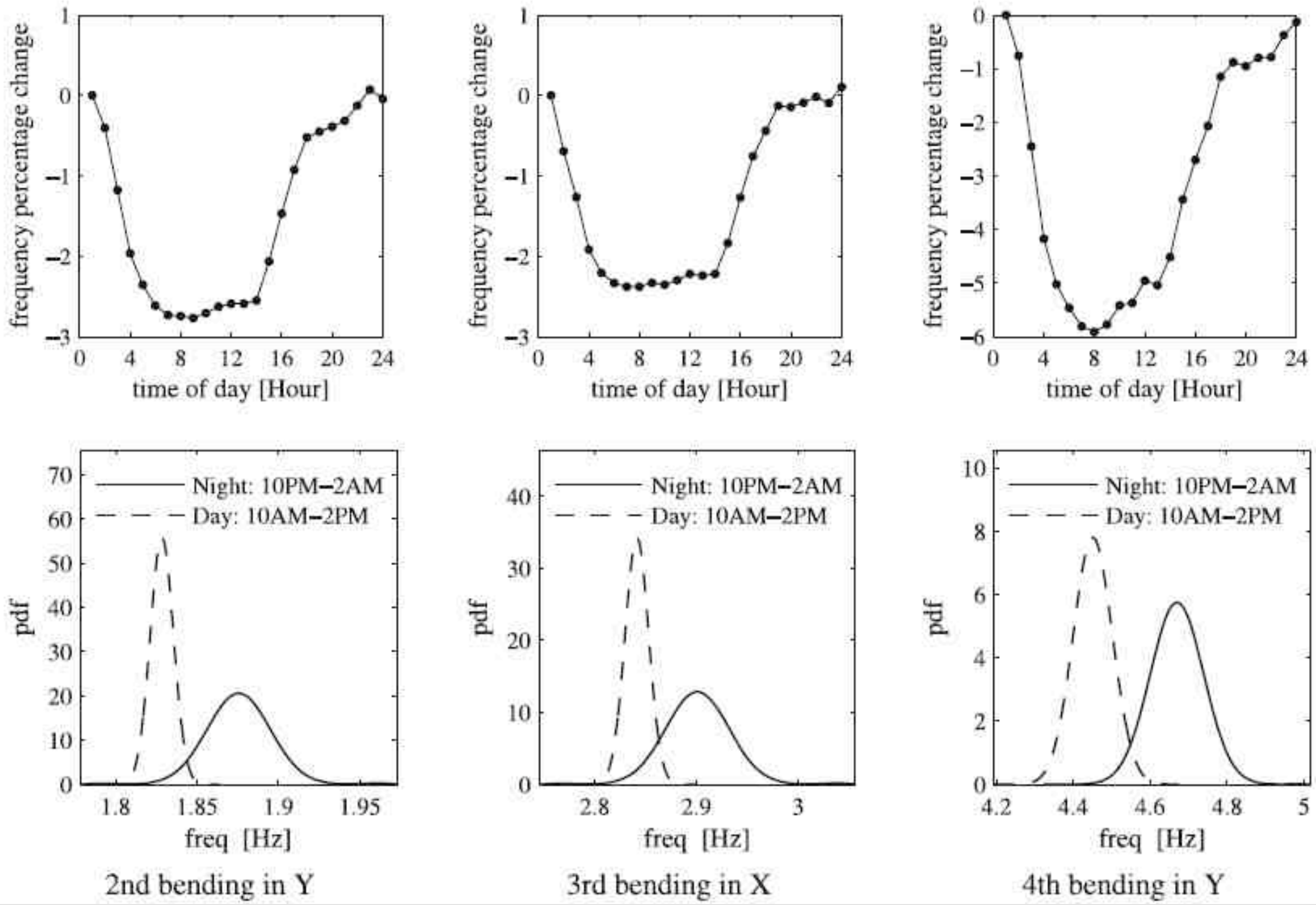


(d) 2nd bending in X

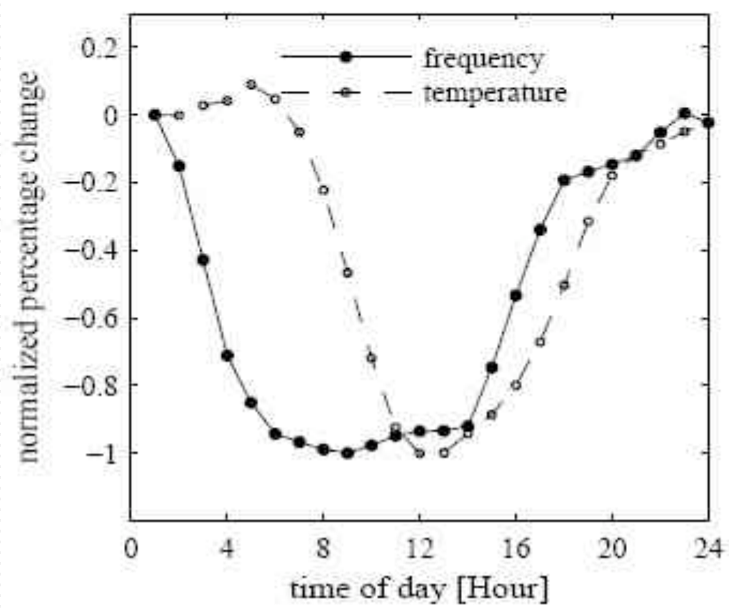
distribution of the estimated modal damping for the Factor Building.

Environmental Variability of Factor Modal Properties from Nayeri, Masri, Ghanem & Nigbor (2008)

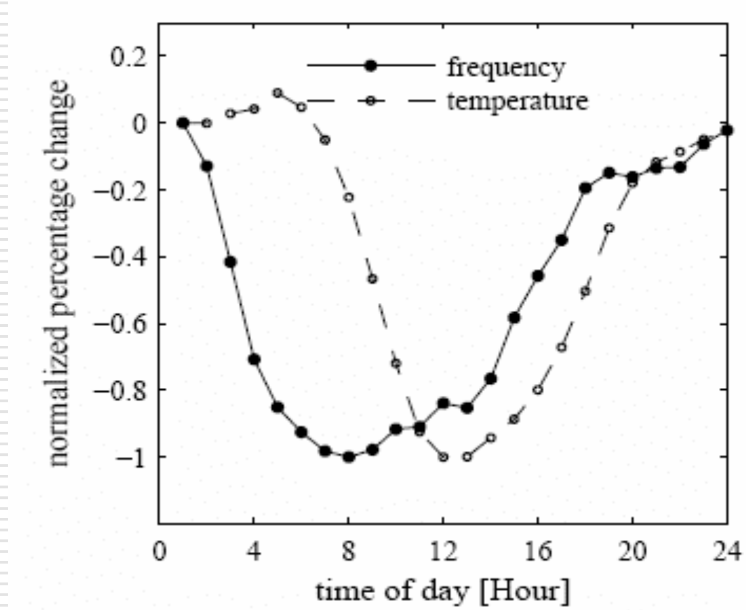
- **50 days of continuous data studied**
- **Daily variation correlates with temperature**
- **Significant time variation in higher modes**



Variability of the Estimated Parameters Due to Temperature Variation

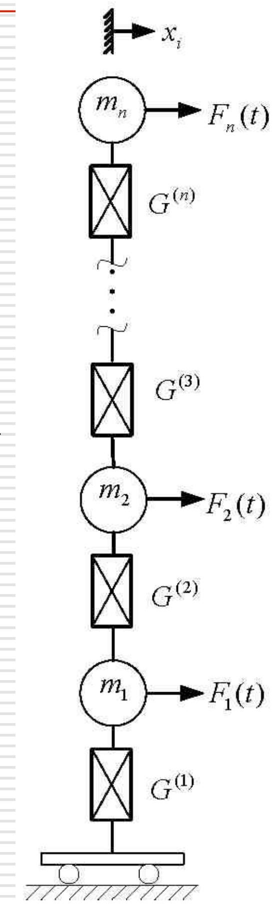


2nd Bending in Y



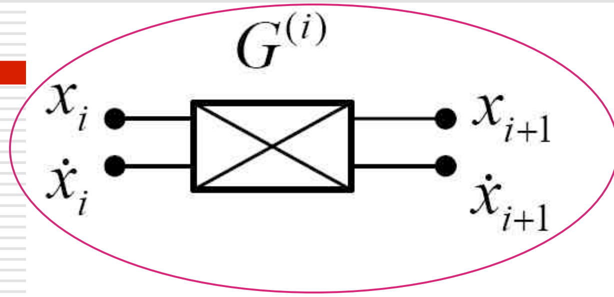
4th Bending in Y

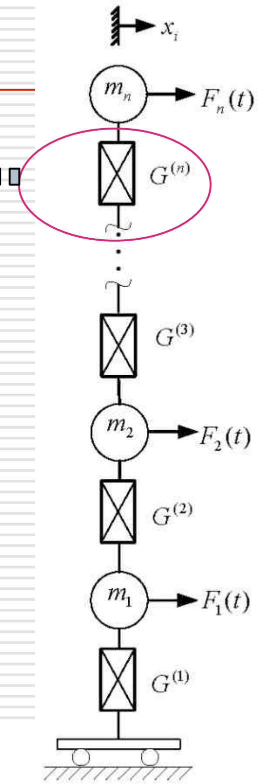
MDOF Chain-like Systems



Model of a MDOF chain-like system

Formulation of the Chain System Identification Approach
General Nonlinear Case:





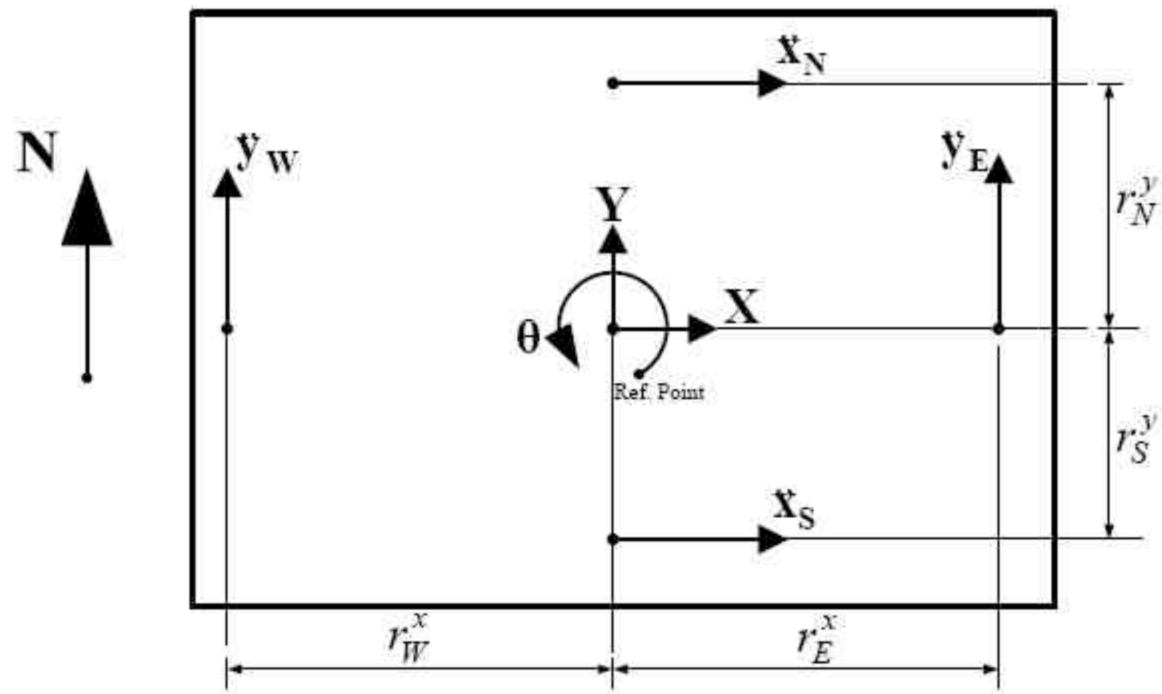
$$z_i = x_{i+1} - x_i$$

$$G^{(i)} = G^{(i)}(p^{(i)}, z_i, \dot{z}_i)$$

$$\begin{aligned} G^{(n)}(\mathbf{p}^{(n)}, z_n, \dot{z}_n) &= F_n(t) - m_n \ddot{x}_n \\ G^{(i)}(\mathbf{p}^{(i)}, z_i, \dot{z}_i) &= F_i(t) - m_i \ddot{x}_i + G^{(i+1)}(\mathbf{p}^{(i+1)}, z_{i+1}, \dot{z}_{i+1}) \end{aligned}$$

$$for\ i = n-1, n-2, \ldots, 1$$

UCLA Factor Building: Instrumentation



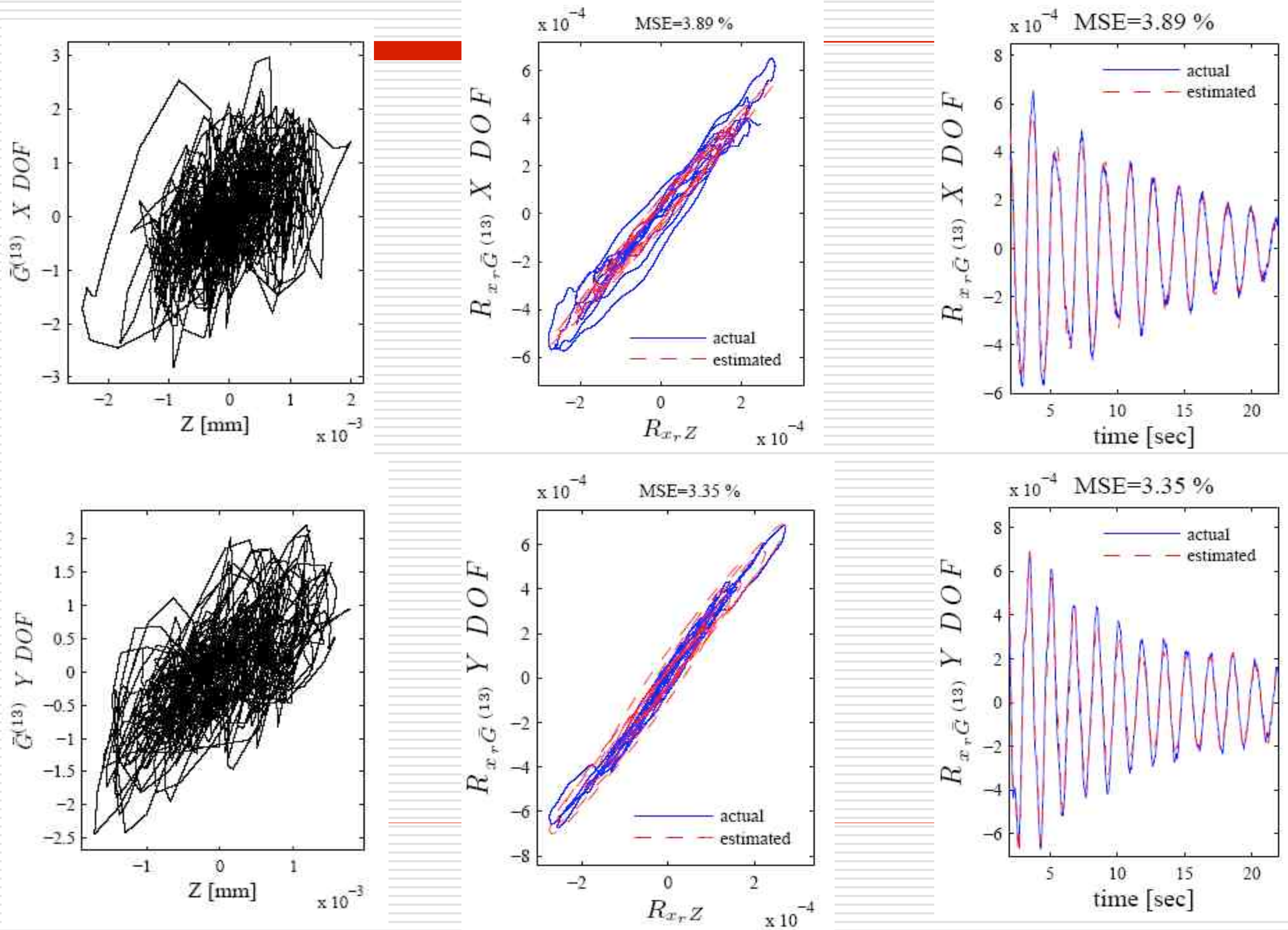
$$\ddot{x} = \frac{\ddot{x}_N + \ddot{x}_S}{2}, \quad \ddot{y} = \frac{\ddot{y}_E + \ddot{y}_W}{2}, \quad \ddot{\theta} = \frac{\ddot{\theta}_x + \ddot{\theta}_y}{2}$$

$$\ddot{\theta}_x = \frac{\ddot{x}_S - \ddot{x}_N}{r_N^y - r_S^y}, \quad \ddot{\theta}_y = \frac{\ddot{y}_E - \ddot{y}_W}{r_E^x - r_W^x}$$

Schematic plot of the sensors layout for each floor above grade

Chain System Identification Results For the Factor Building

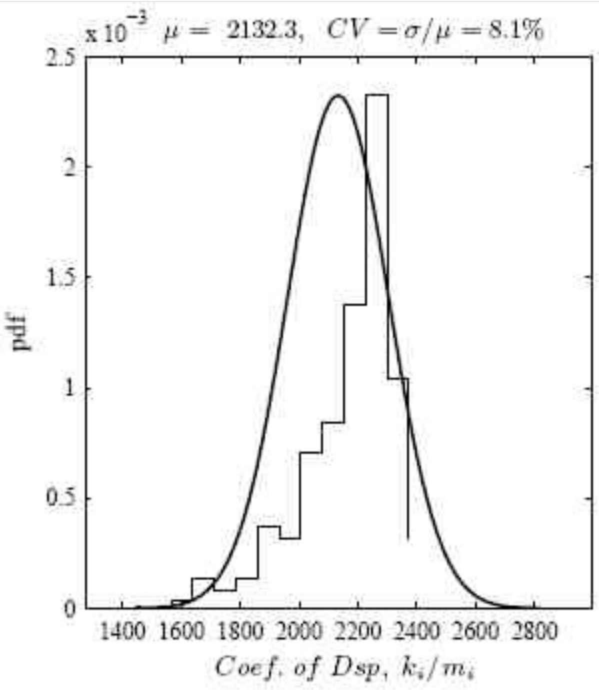
Representative phase and time-history plots of the restoring force functions associated with the 13th floor of the factor building, in x and y directions



Chain System Identification Results For the Factor Building

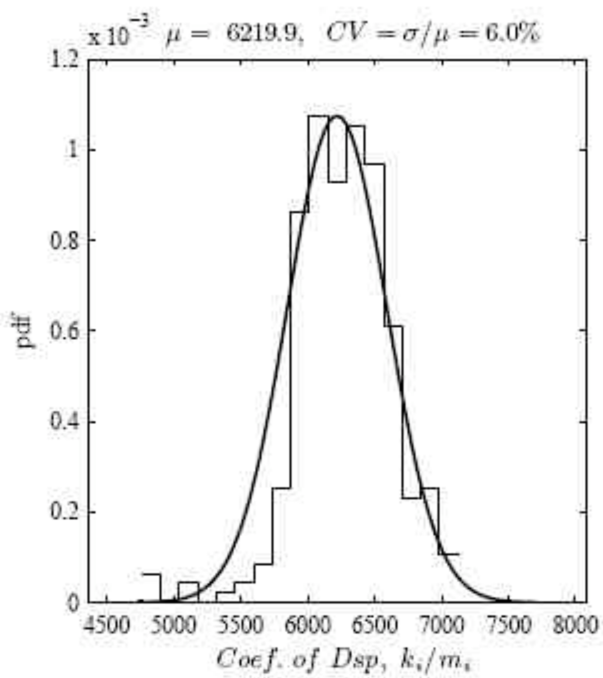
Sample distributions of the estimated coefficient of **displacement** term in the interstory restoring functions. Coefficient of **displacement** is the **mass-normalized stiffness term (k/m)**. The chain identification was performed over a time-window interval of 2 hours, and with 50% overlap, for a total number of 50 days.

.



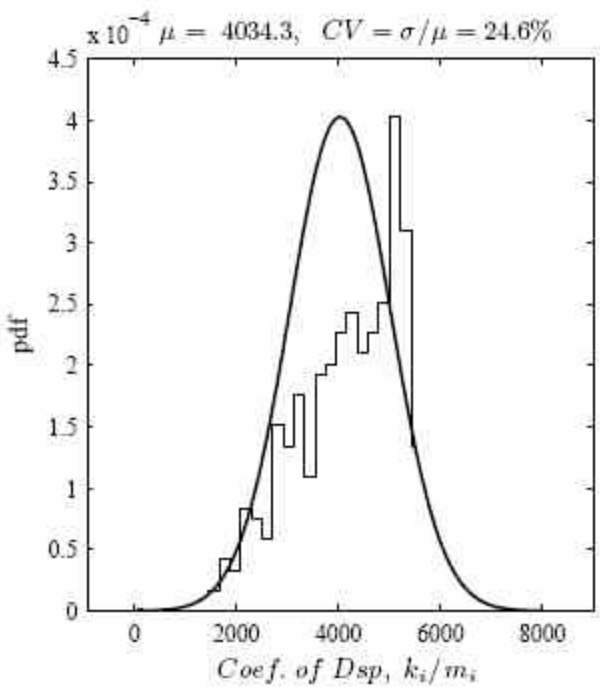
(a) 2nd floor, x

X direction



(b) 2nd floor, y

Y direction



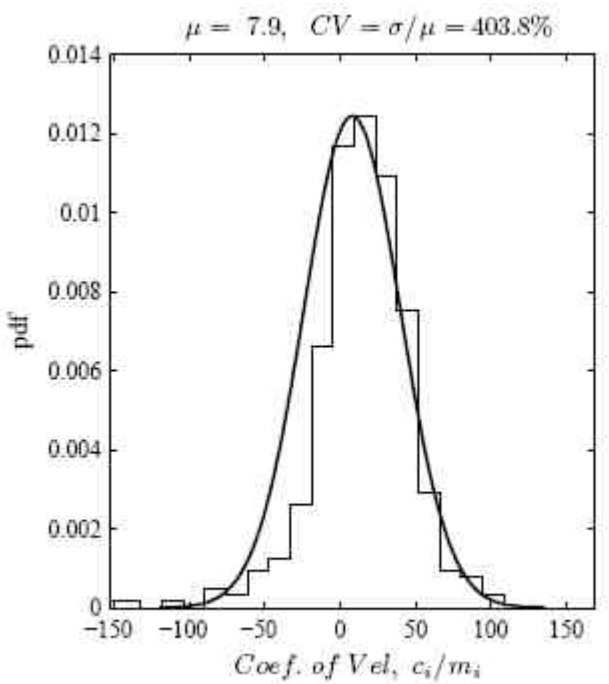
(c) 2nd floor, θ

theta direction

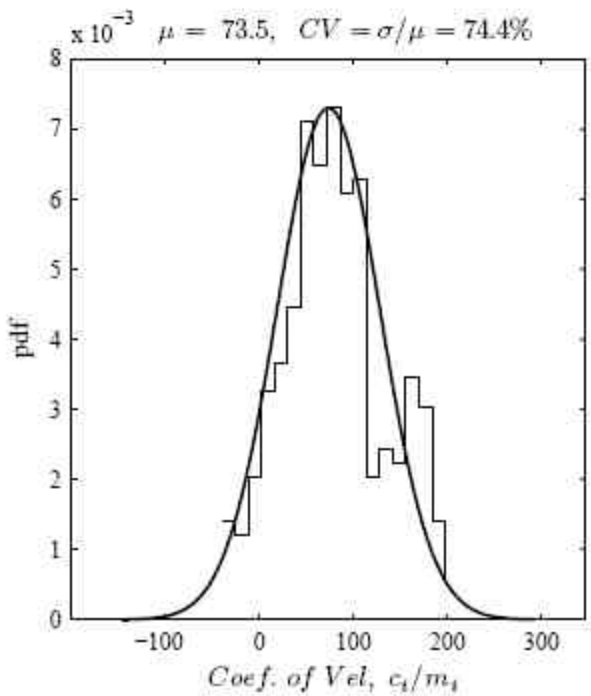
Chain System Identification Results For the Factor Building

Sample distributions of the estimated coefficient of **Velocity** term in the interstory restoring functions. Coefficient of **Velocity** is the **mass-normalized damping term (c/m)**. The chain identification was performed over a time-window interval of 2 hours, and with 50% overlap, for a total number of 50 days.

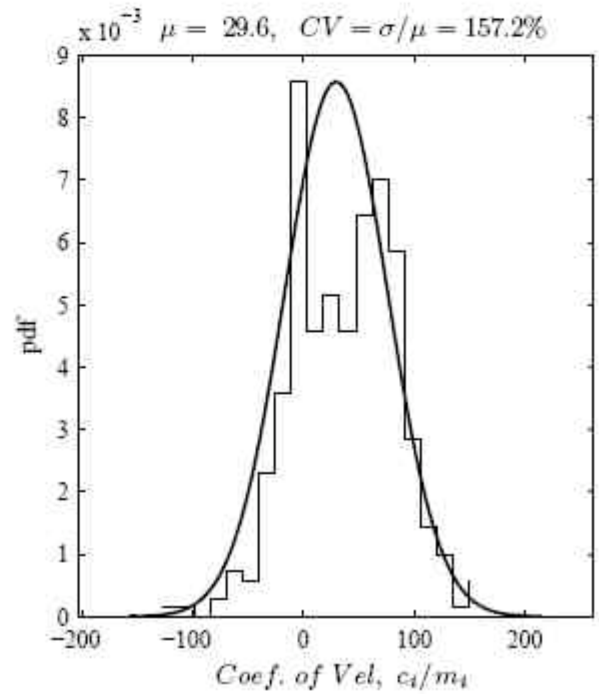
.



(a) 2nd floor, x



(b) 2nd floor, y



(c) 2nd floor, θ

X direction **Y direction** **theta direction**

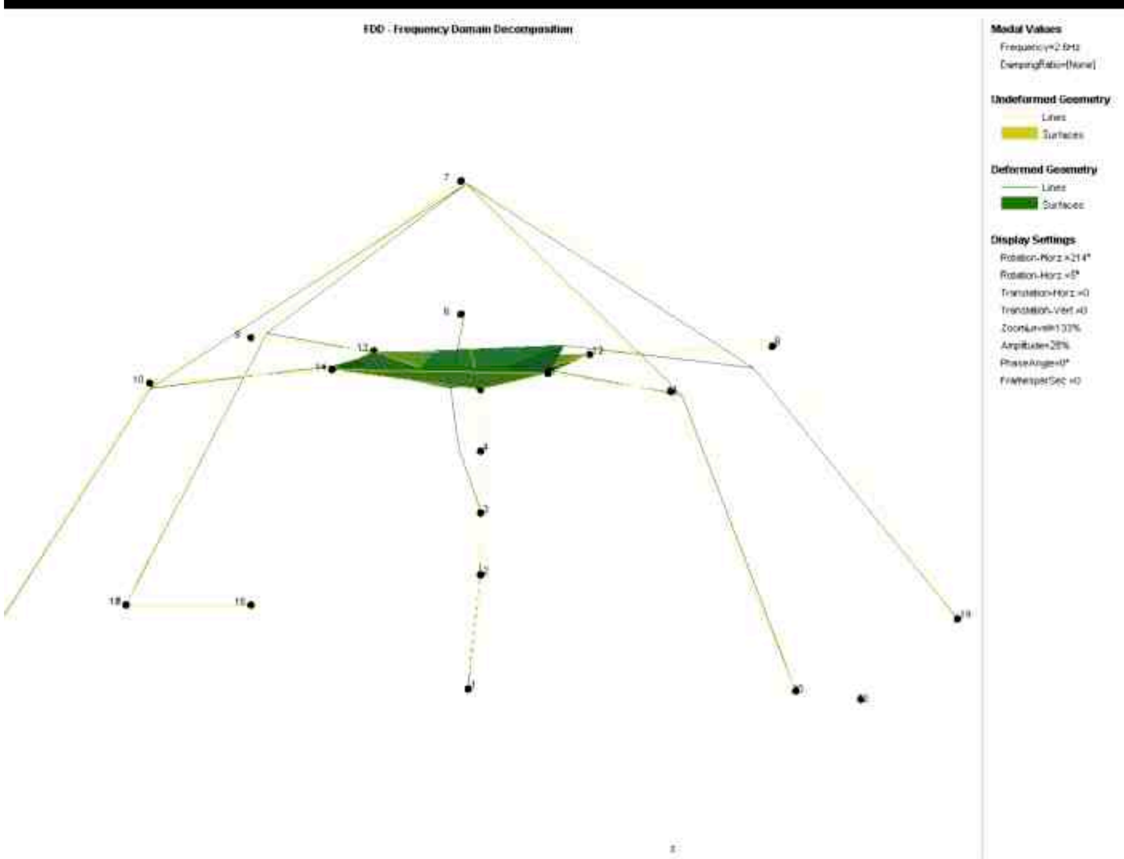
Import Result for SHM: Variability of the Estimated Parameters Due to Environmental and Other Effects

There are many sources other than damage that can cause noticeable variations in the estimated (identified) dynamic properties of a structure. These sources of variation can be divided into three main categories:

(1) environmental conditions such as temperature variation, soil condition, and humidity

(2) operational condition, such as traffic conditions and excitation sources

(3) measurement and processing errors, including nonstationarity, measurement noise and hysteresis, and errors associated with digital signal processing.



FDD - Frequency Domain Decomposition
Modal Values
Undeformed Geometry
Lines
Surfaces
Deformed Geometry
Lines
Surfaces
Display Settings

LAX Theme Building Assessment

Los Angeles World Airports
LAX - Theme Building Restoration

nees@UCLA

miyamoto. STRUCTURAL & EARTHQUAKE ENGINEERING

GWA

VCA Engineers Inc.

CSA Constructors

LAX Theme Building Monitoring by UCLA

- EMA (Experimental Modal Analysis) done before & to be done after seismic retrofit of the structure
- The purpose of EMA is to measure the dynamic properties of a real structure for comparison with and validation of computer models of the structure
  - Mode Frequencies
  - Mode Damping
  - Mode Shapes
  - Transfer Functions
- Permanent real-time monitoring to be installed for earthquake and SHM research

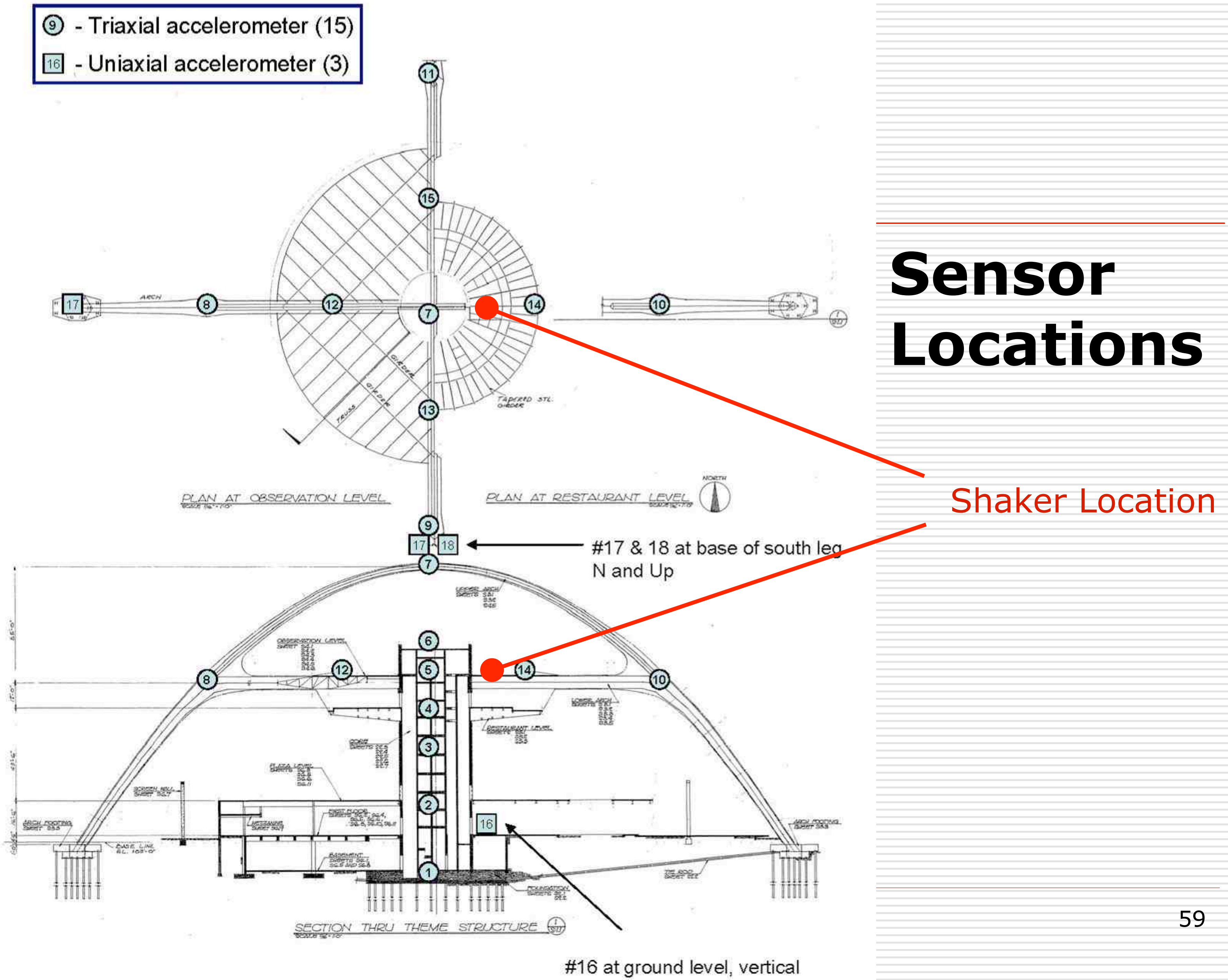
Theme Building Experimental Modal Analysis

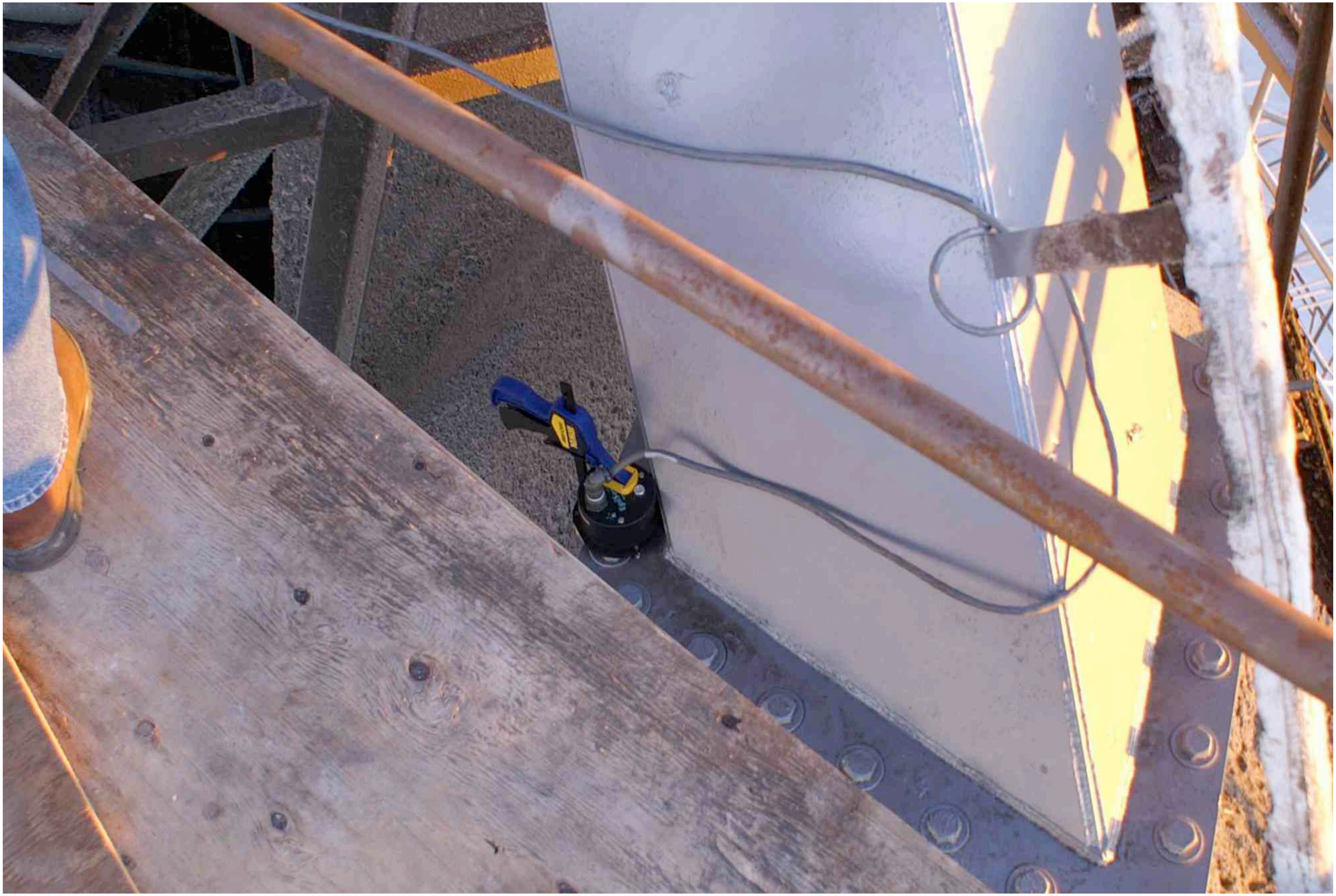
- The LAX Theme Building is a uniquely difficult structure to model:
  - Complex geometry
  - Complex connections
  - Older materials
- EMA adds confidence to the modeling of earthquake and wind response
- EMA estimates in-situ damping
- EMA helps in the design of the proposed TMD system

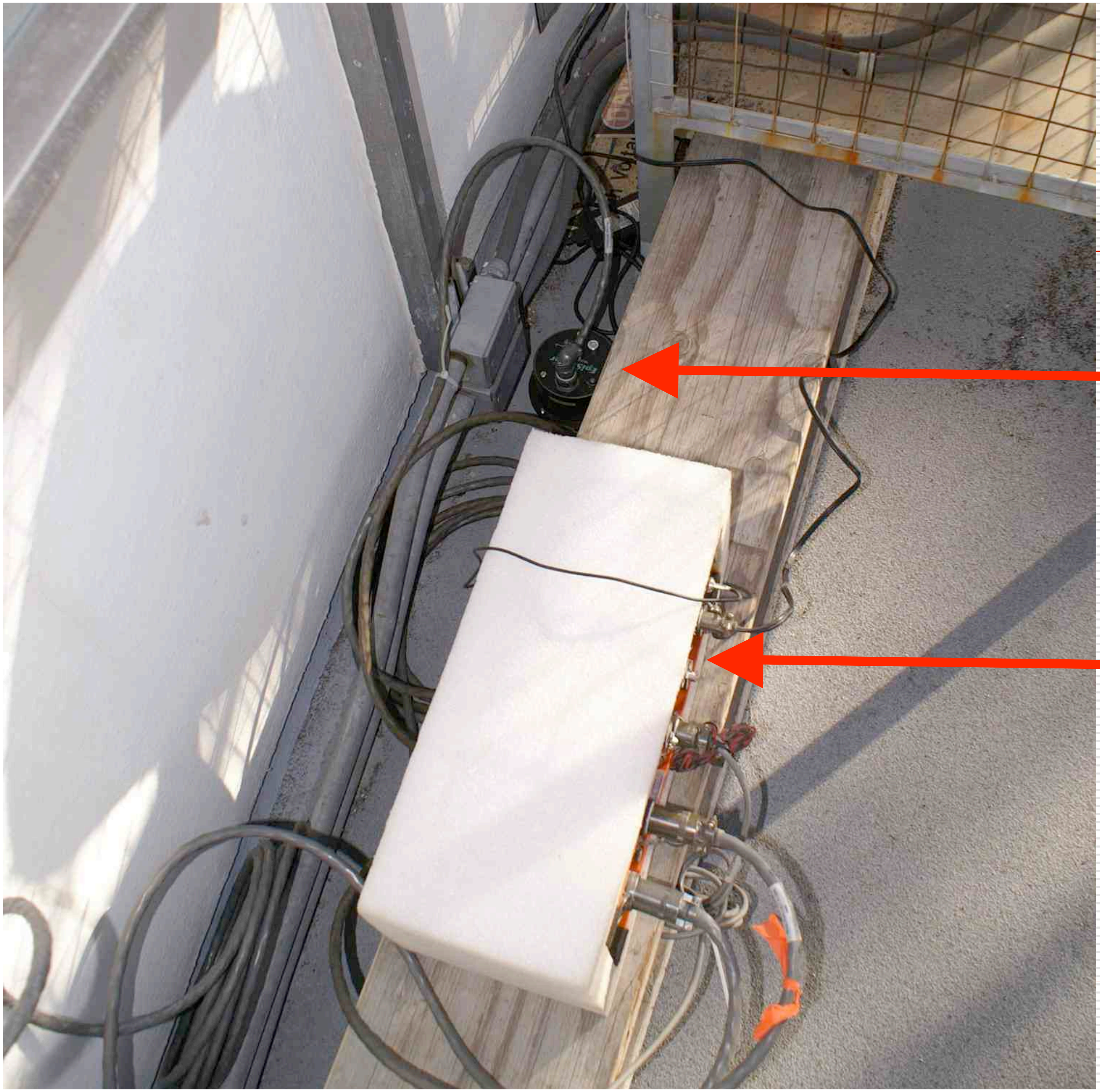
Measurements

- UCLA's small shaker, with 10,000 lb maximum force, installed on east side of observation deck. Force set to (100 x f^2) lbs.
- 51 channels of accelerometers installed at 18 locations
- Very high resolution digital recording to measure ambient through earthquake levels (micro-g to 2g)

Sensor Locations







Sensor

Recorder

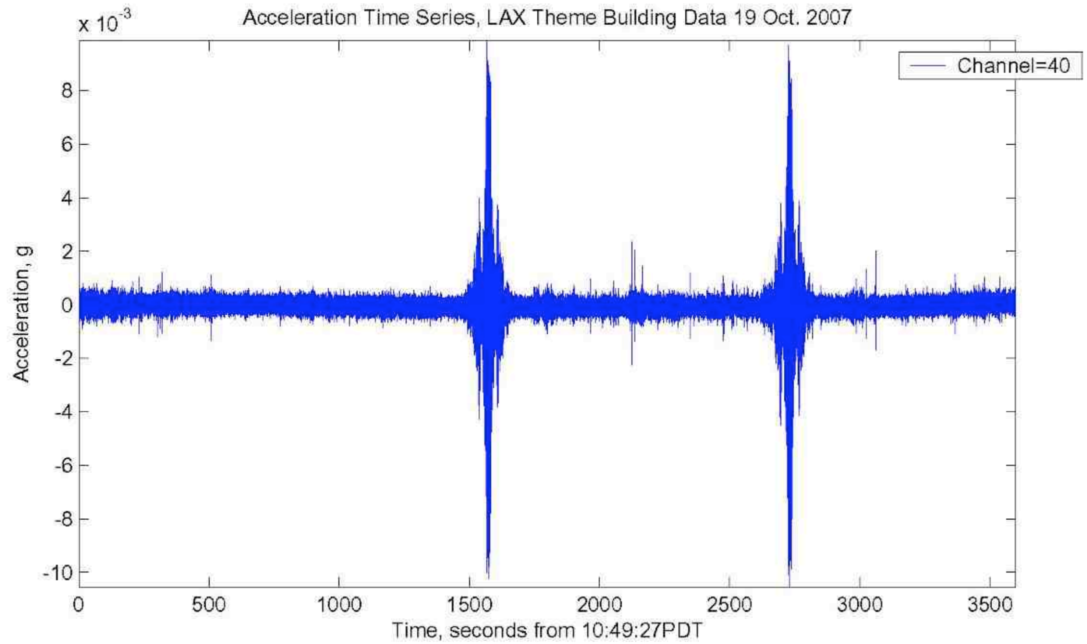
Data Recording

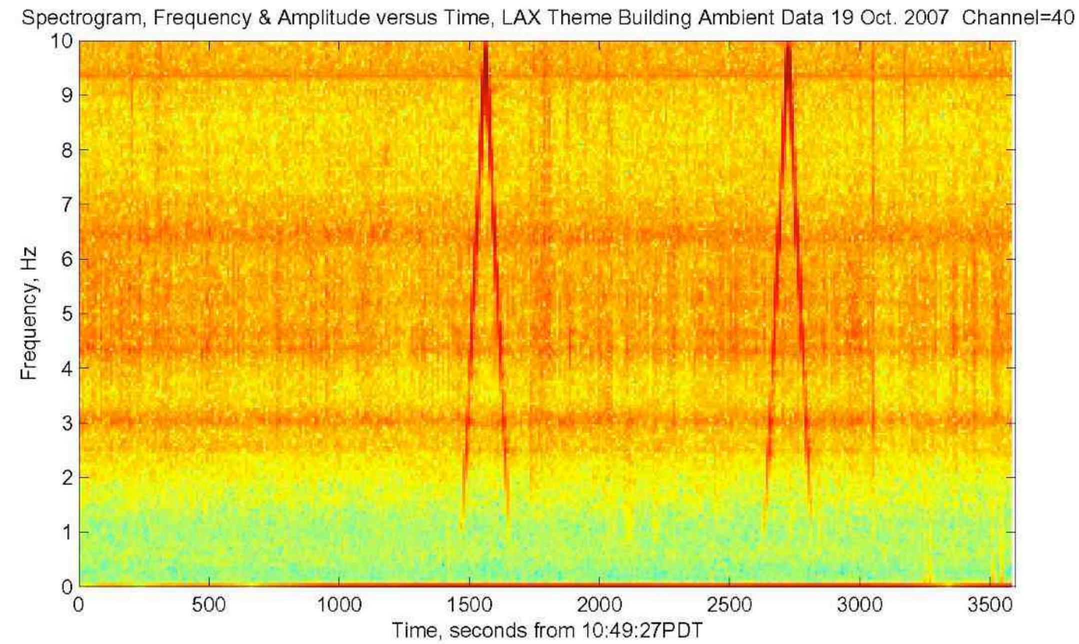
- Thursday Oct. 18: Installation
- Friday Oct. 19: E-W (X) shaking
- Friday–Sunday: Ambient Vibration, Santa Ana winds on Saturday Oct. 20 evening to 20 mph
- Monday Oct. 22: N-S and E-W shaking
- Monday–Friday: Ambient vibration, continuous

Sample Data:

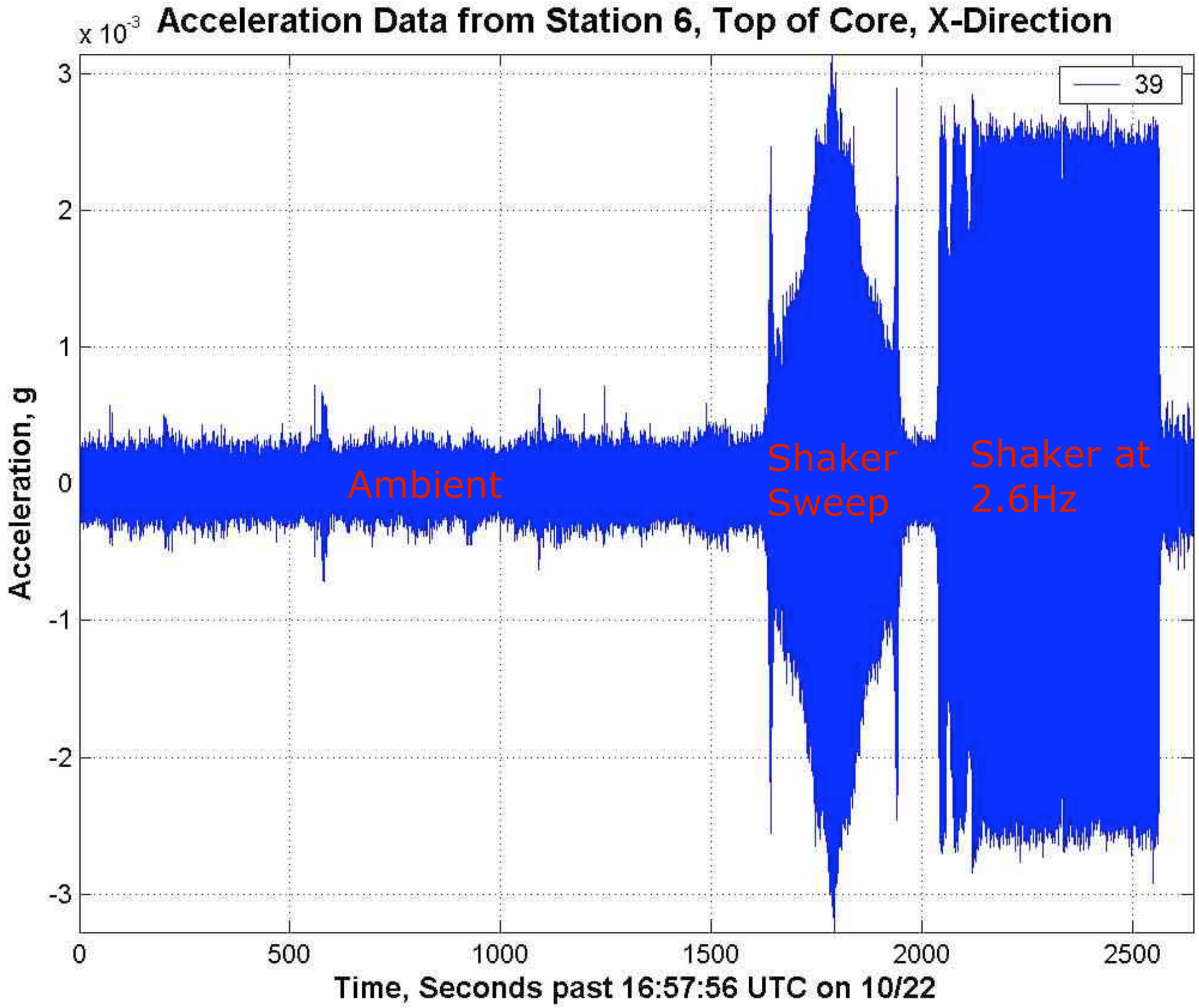
Location 14, observation deck, vertical,
1-hour, ambient & shaking

Peak~0.01g

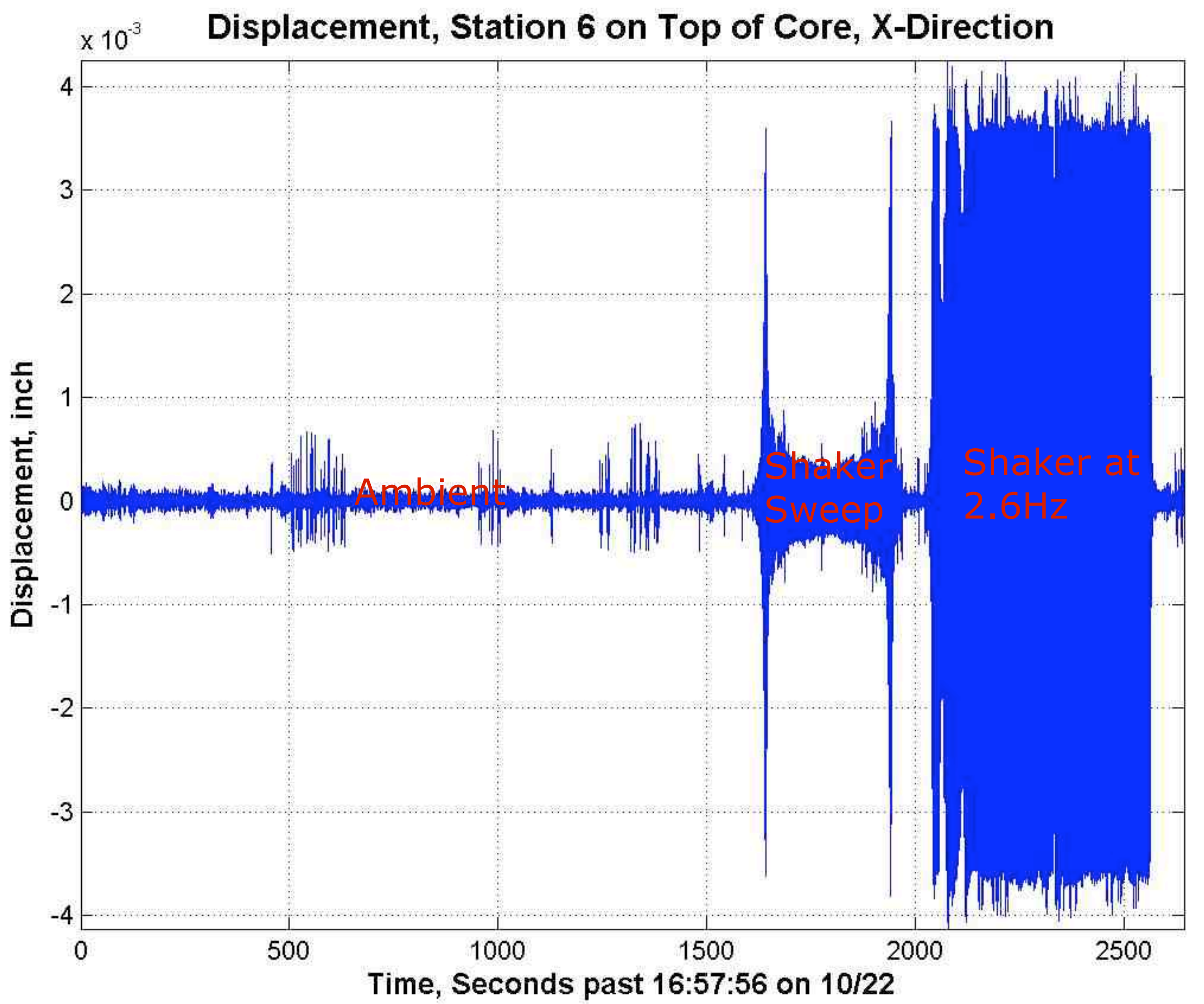




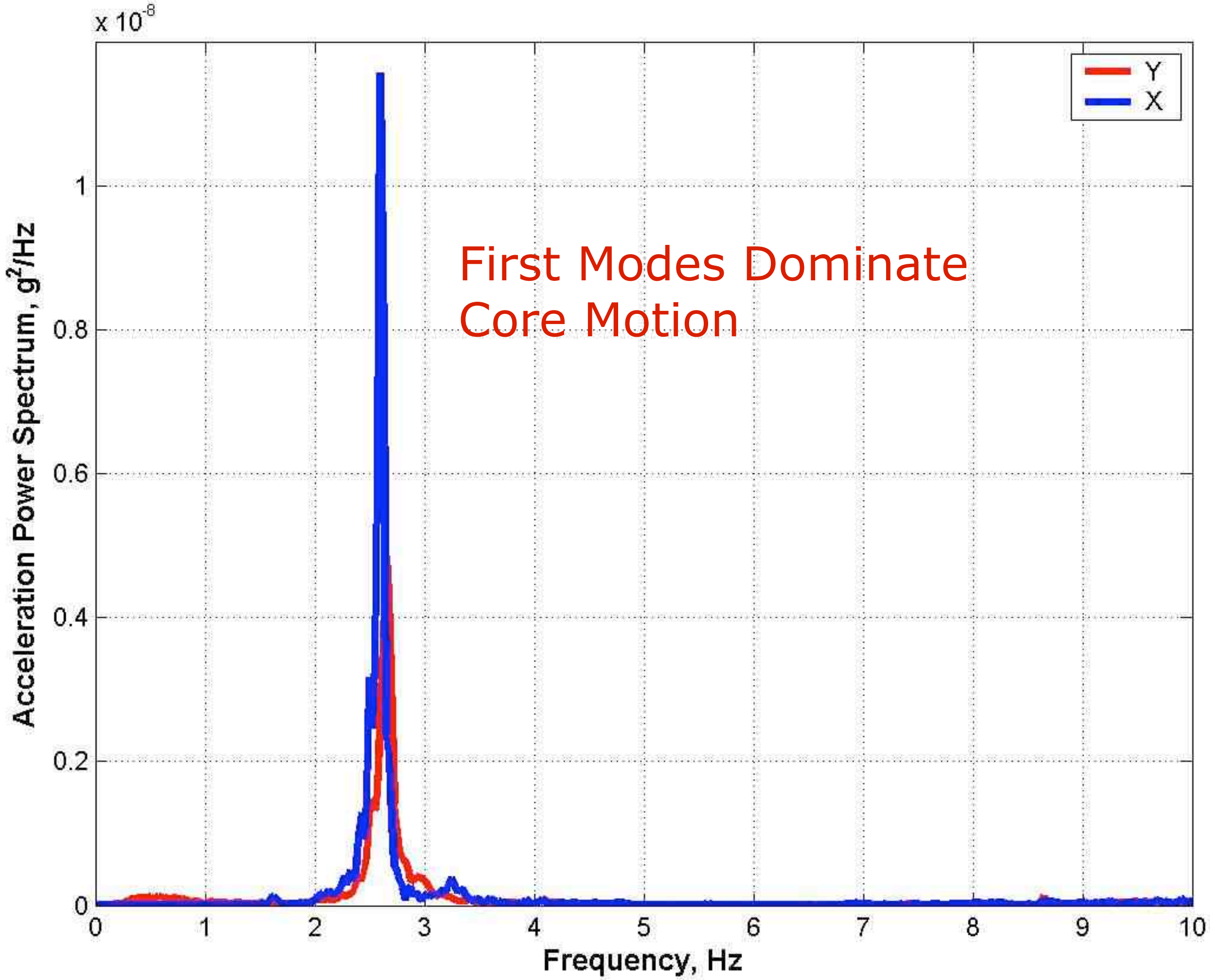
Sample Data, Acceleration (g)



Sample Data, Displacement (inch)

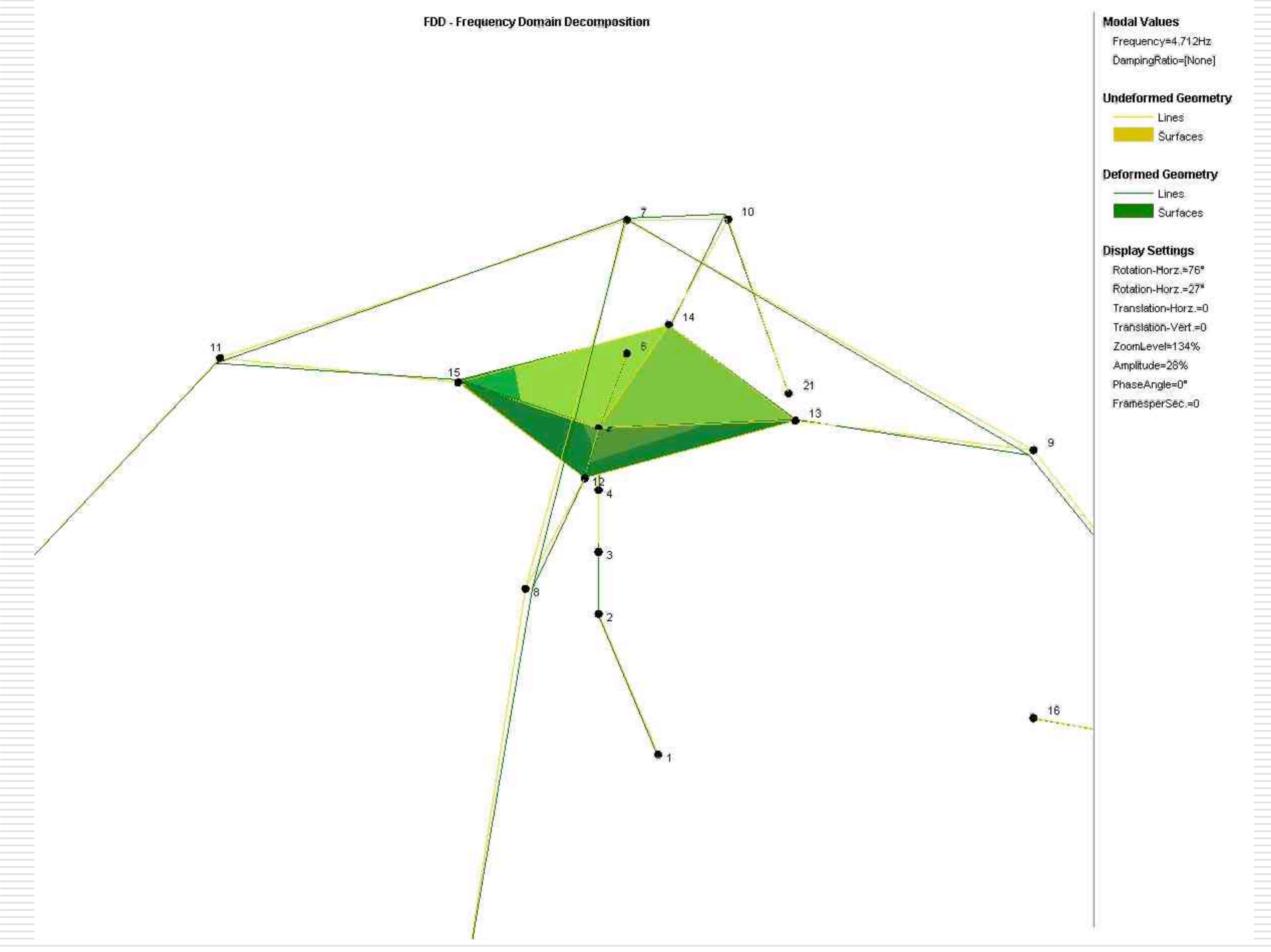


Sample Ambient Vibration Spectra, Top of Core, X and Y Directions



Results

Frequency	Shape	Damping, Ambient	Damping, Shaker
2.5	E-W	1%	5%
2.7	N-S	2%	5%
4.7	Torsion + Legs		
5.7	Legs		
7.0	E-W		
9.4	N-S		


FDD - Frequency Domain Decomposition
Modal Values
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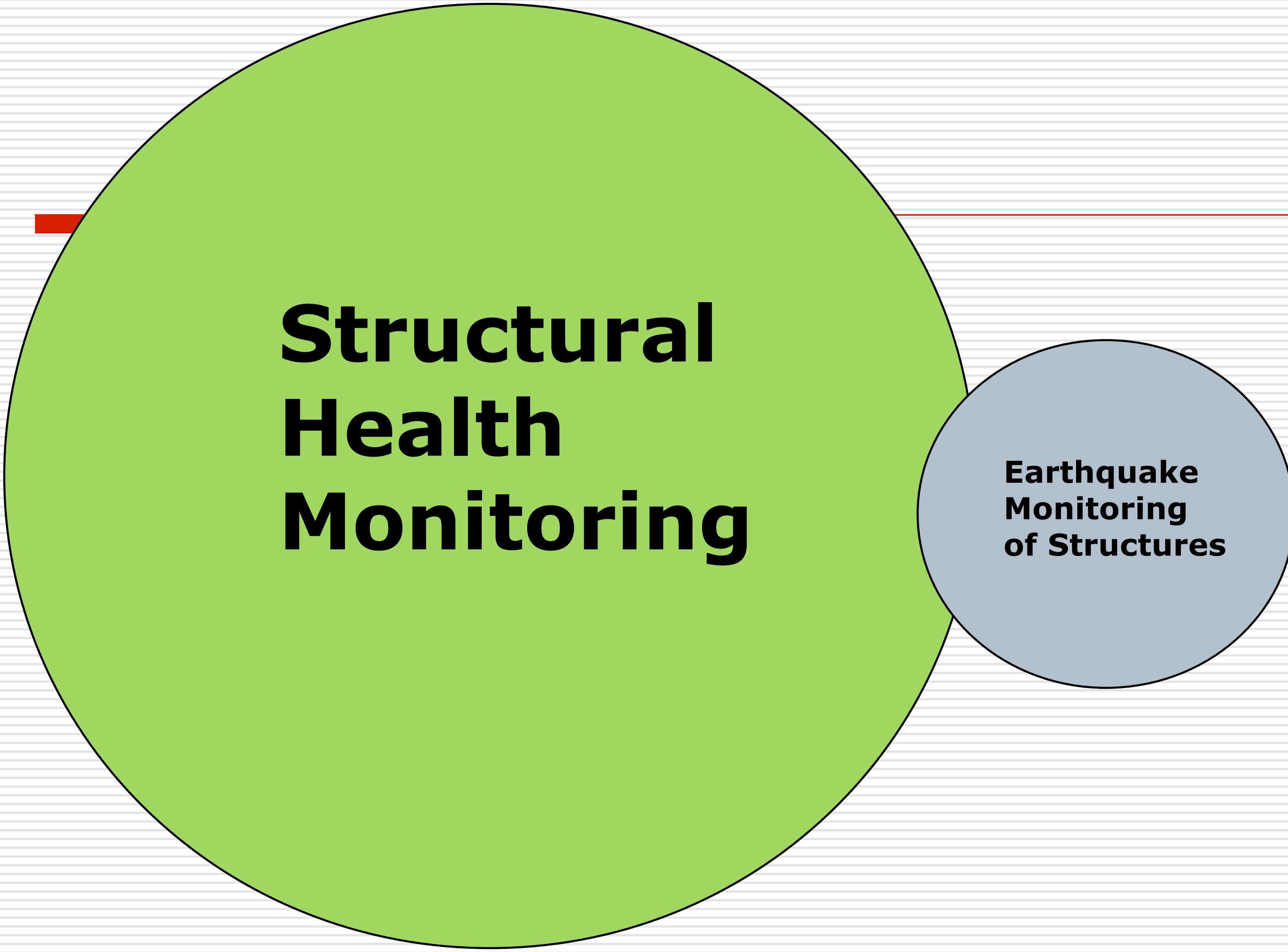
Undeformed Geometry
Lines
Surfaces
Deformed Geometry
Lines
Surfaces
Display Settings
Rotation-Horz.=76°
Rotation-Horz.=27°
Translation-Horz.=0
Translation-Vert.=0
ZoomLevel=134%
Amplitude=28%
PhaseAngle=0°
FramesperSec.=0
7
10
14
11
6
15
21
13
9
12
4
3
8
2
16
1


Structural
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Earthquake
Monitoring
of Structures