Developing Practical Dynamic Evaluation Methods for Transportation Structures

C.J. Riley, PhD, PE

Associate Professor of Civil Engineering

Oregon Institute of Technology

About Me

- BS Engineering, Swarthmore College, 2001
- MS Civil Engineering, Colorado State University, 2003
- Wyoming DOT Bridge Program 2003-2005
  - BRASS
  - Design checking
  - Bridge inspection and management
- PhD Civil Engineering, Colorado State University, 2009
- Oregon Tech Faculty 2008-present
- 24 courses developed and delivered

How This Started

- Civil engineering BS/MS program development at Oregon Tech
- Courses in Bridge Rating, Bridge Design, Transportation Structures, Structural Dynamics, and Advanced Mechanics
- Hands-on: exploring lab, field, and demonstration-driven teaching methods
- Borrowed a shake table from Oregon State U that did not have a functional data collection system
- Recognizing that my phone had a 3-axis accelerometer in it, we used iPhone data collection on shake table models for the first offering of CE535 Structural Dynamics with excellent results

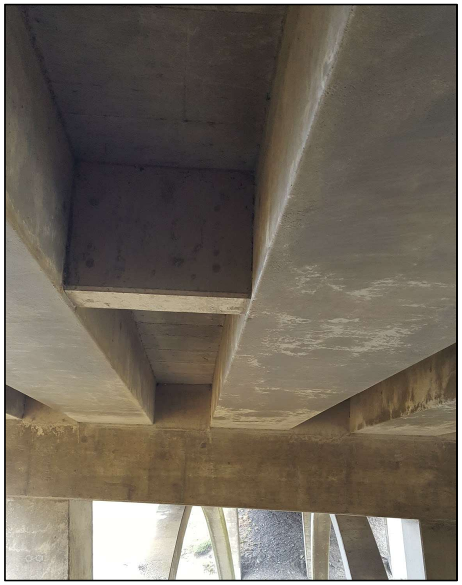
How this all started

- Data collection by mobile device was about as good as I had experienced in previous work
- Good enough for the lab!
- Good enough for the field?

The Big Goal(s)

- Of structural Health Monitoring (SHM) broadly
  - Continuous, periodic, one-time evaluation
  - Local or global behavior/damage
  - SHM categories (Webb et al 2015):

    Anomaly detection, sensor deployment, model validation, threshold check, damage detection
- This work
  - A simple, easily-deployed system to generate useful data
  - Motivated by the Cascadia quake and resiliency goals
  - A big data set to drive refinements in bridge management/design/rating for dynamic hazards – specifically in-service natural frequency data for all state bridges



Learning Outcomes

- Describe the scale of the everyday and future hazards facing Oregon bridges
- Explain the relationship of structural parameters to dynamic response
- Describe a framework for conducting dynamic evaluation of structures to determine dominant modal frequencies
- Summarize the results of preliminary field studies using ambient traffic and forced vibration in conjunction with mobile-device based data acquisition
- Use mobile devices and apps to acquire acceleration data

Oregon's Bridges: More than 8,000 strong

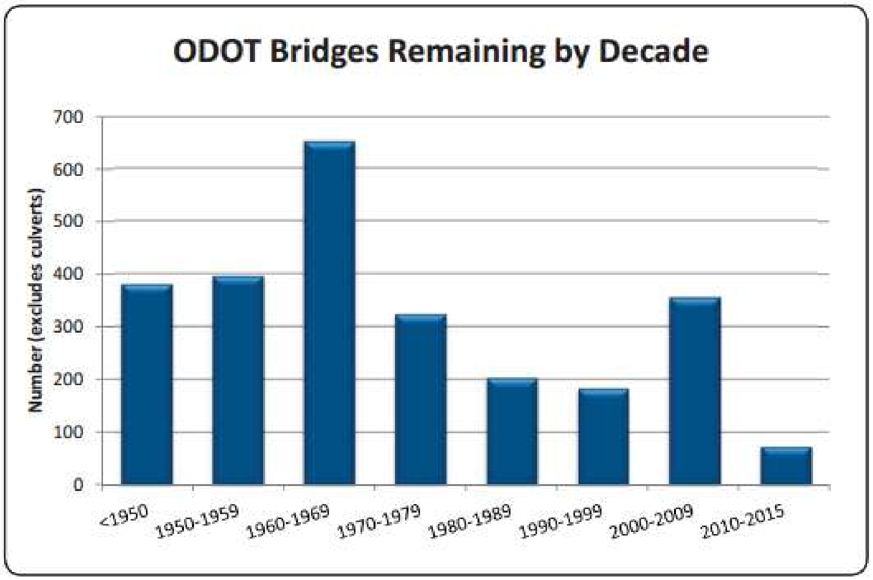
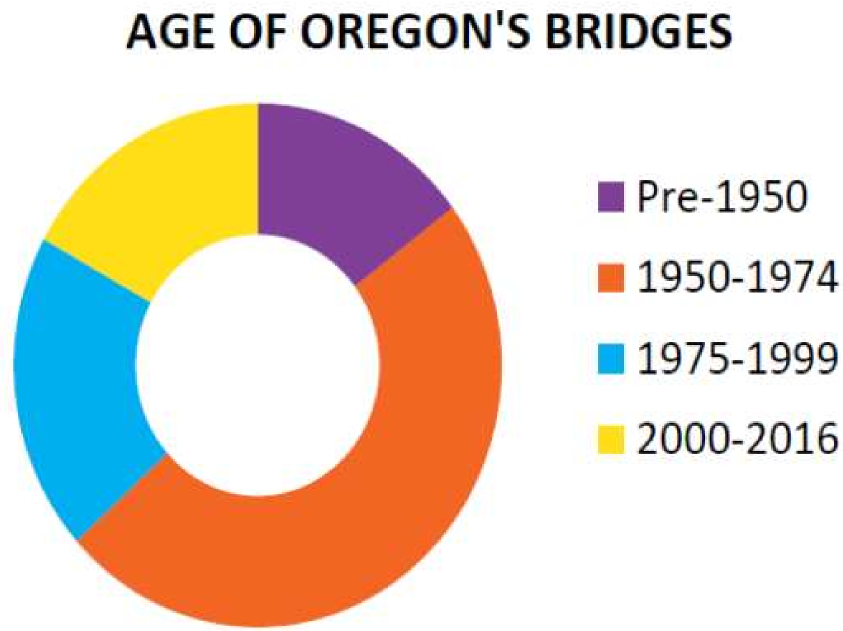


Figure 2. More than half of Oregon's bridges were built prior to 1970, and more than 1,000 were built during the Interstate-era.



ftp://ftp.odot.state.or.us/Bridge/bridge_website_chittirat/EXEC_Summary_Final_2016_Bridge_Tunnel_Report_091316.pdf

https://oregontransportationforum.files.wordpress.com/2017/05/jointtransportationreport.pdf

Condition of Oregon's Bridges: 5.5% SD

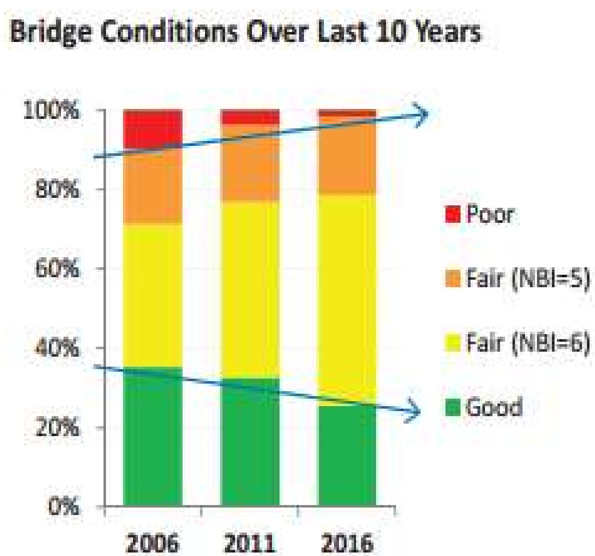


Figure 1. Bridge Condition over last 10 years

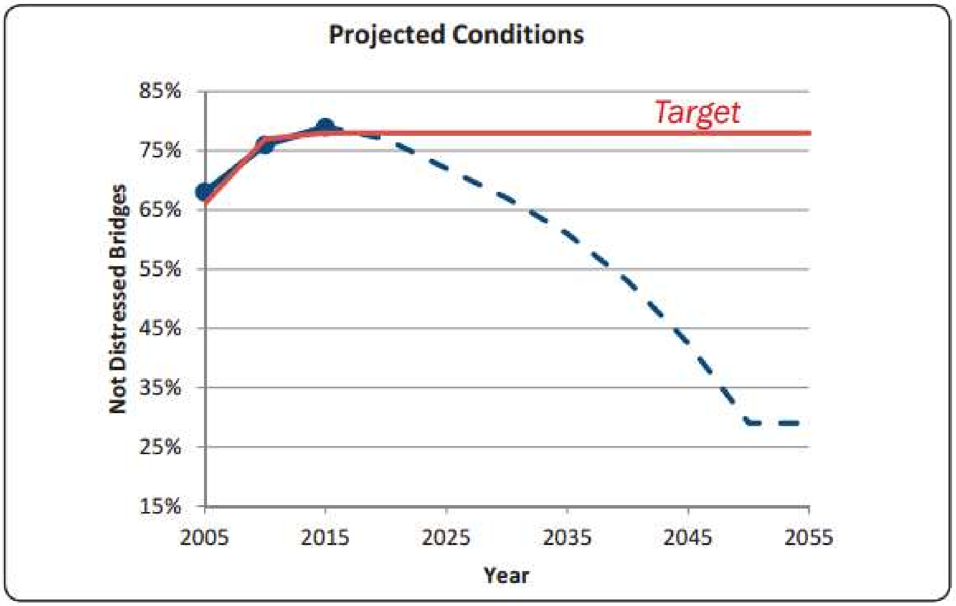


Figure 3. Based on general conditions, the percentage of non-distressed bridges is projected to decline steadily.

ftp://ftp.odot.state.or.us/Bridge/bridge_website_chittirat/EXEC_Summary_Final_2016_Bridge_Tunnel_Report_091316.pdf
https://oregontransportationforum.files.wordpress.com/2017/05/jointtransportationreport.pdf

Oregon’s Bridges – Cascadia Subduction Zone

- Magnitude 8.3-9.0
- ~3 minutes of shaking
- Full-rip, half-rip scenarios

- Damage throughout Oregon
- Significant damage along coast and I-5 routes

Cascadia Subduction Zone Setting

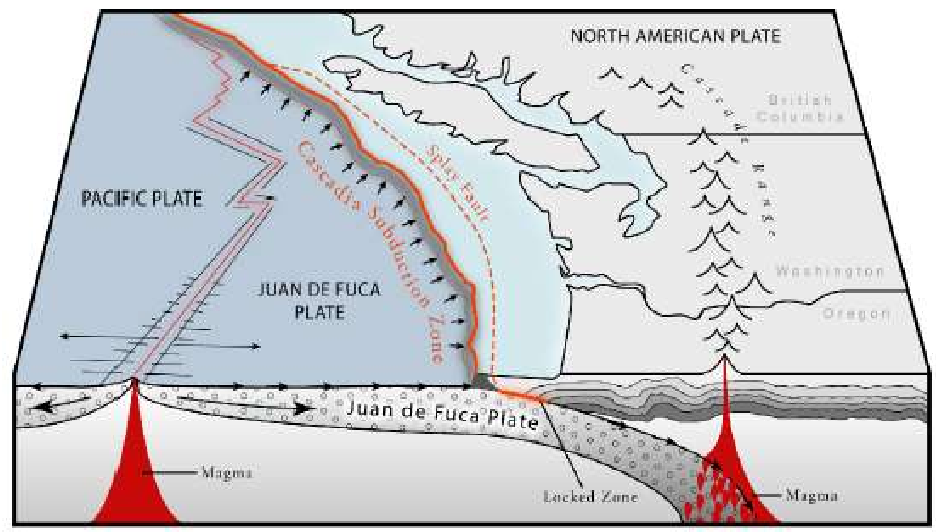
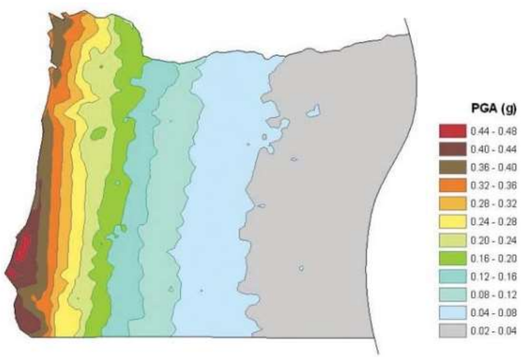
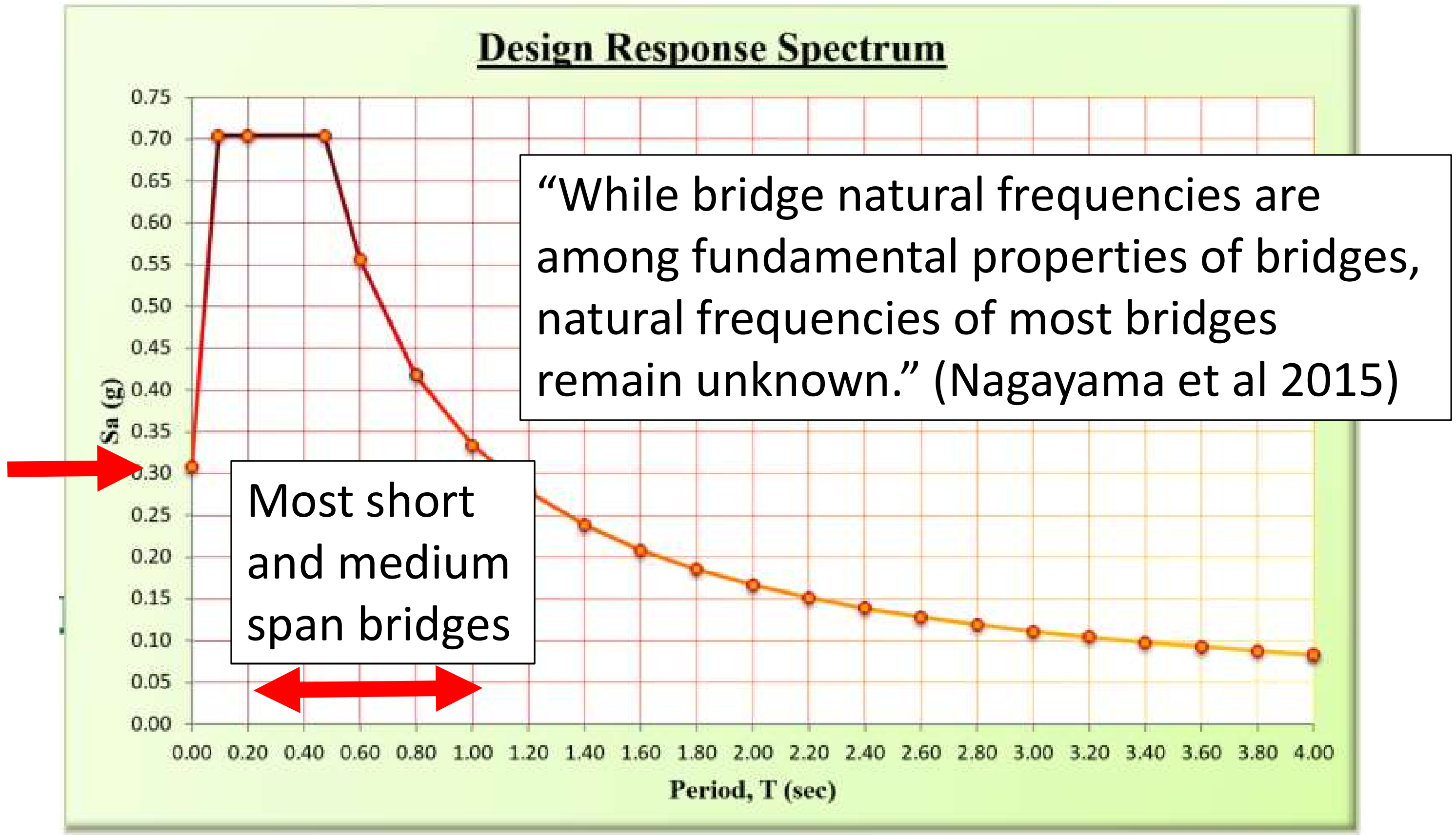


Figure 1: This block diagram depicts the tectonic setting of the region. See Figure 2 for the sequence of events that occur during a Cascadia Subduction Zone megathrust earthquake and tsunami.

http://www.oregongeology.org/pubs/tim/p-TIM-overview.htm

Designing for Probabilistic and Deterministic Hazards





"While bridge natural frequencies are among fundamental properties of bridges, natural frequencies of most bridges remain unknown." (Nagayama et al 2015)

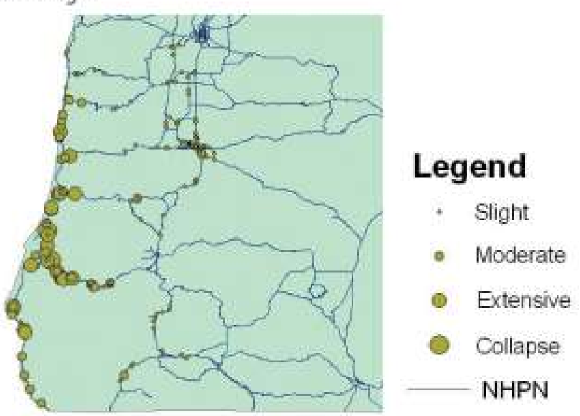
Most short and medium span bridges

ODOT Seismic Vulnerability (2009) and Seismic Plus (2014) Studies

Cascadia Subduction Zone Earthquake near Southern Oregon

An earthquake scenario of magnitude 8.3 at the Cascadia Subduction Zone near Southern Oregon produced 2 complete collapses, 23 extensive, 33 moderate and 123 slight damage states. The losses evaluated were $363 million for bridge repair and replacement and $94 million travel time related losses. *Figure 5.8* shows a map of component damage states for the southwestern part of Oregon.

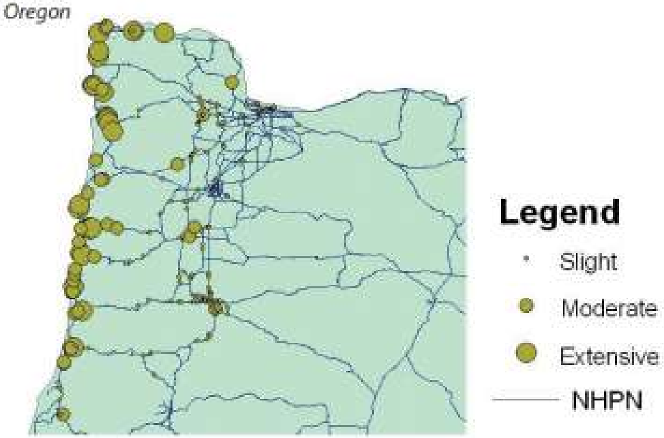
Figure 5.8 : Component Damage States for a Magnitude 8.3 Cascadia Subduction Zone Scenario EQ near southern Oregon



Cascadia Subduction Zone Earthquake near Northern Oregon

An earthquake scenario of magnitude 8.3 at the Cascadia Subduction Zone near northern Oregon produced no complete collapses, 28 extensive, 32 moderate and 152 slight damage states. The losses evaluated were $336 million for bridge repair and replacement and $8 million travel time related losses. *Figure 5.9* shows a map of component damage states for the northwestern part of Oregon.

Figure 5.9 : Component Damage States for a Magnitude 8.3 Cascadia Subduction Zone Scenario EQ near northern Oregon



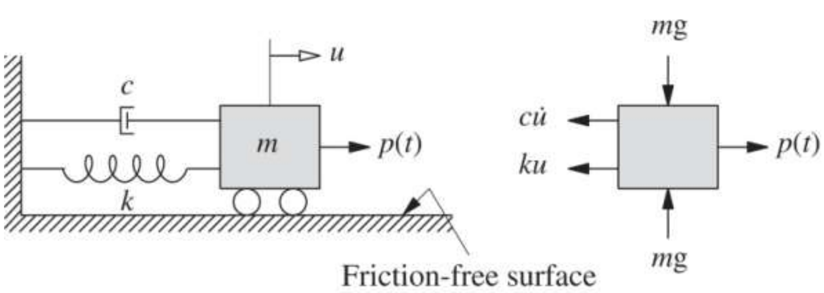
Basics of Structural Dynamics

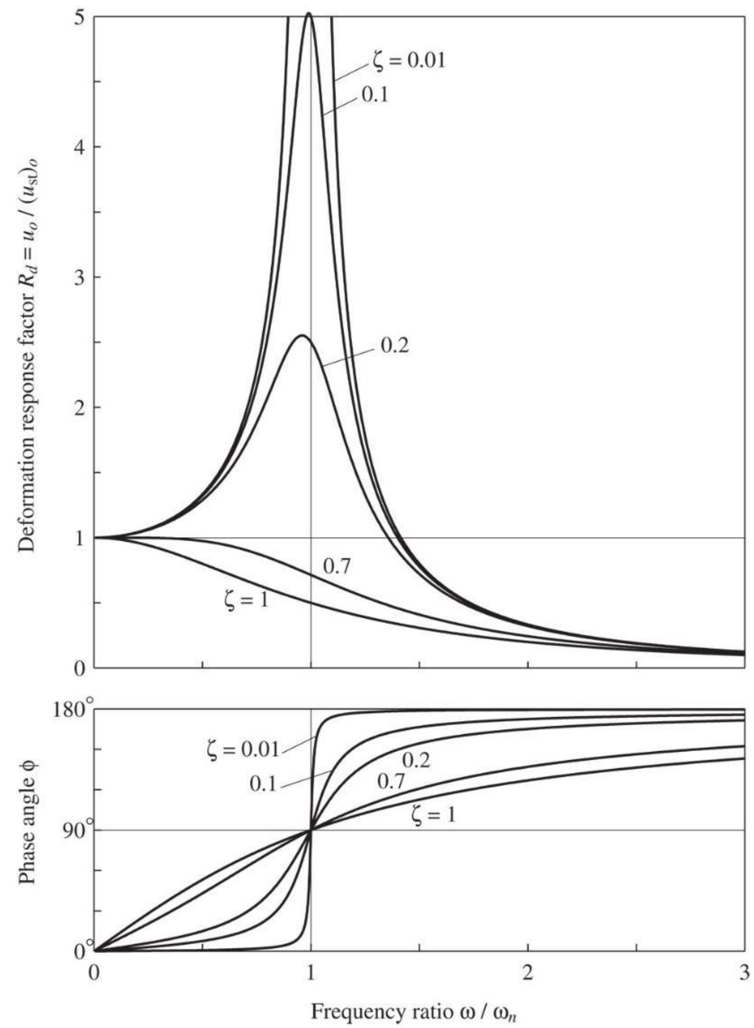
The natural frequency of a lumped mass structure, ω_n (rad/s), is related to its mass, m, and stiffness, k

$$\omega_n = \sqrt{\frac{k}{m}}$$

The natural period (sec) and natural frequency (Hz) are similarly related

$$T_n = \frac{1}{f_n} = \frac{2\pi}{\omega_n}$$





Basics of Structural Dynamics

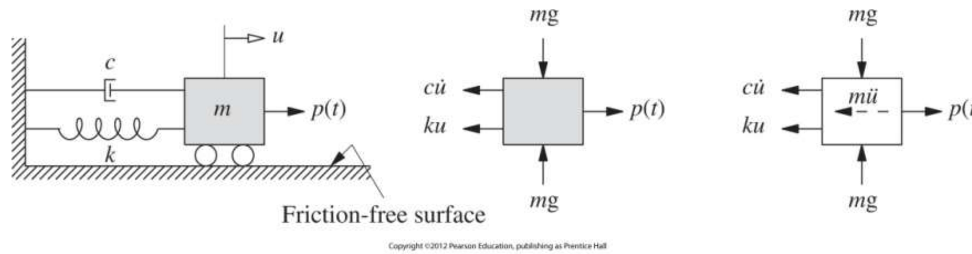
Types of Models

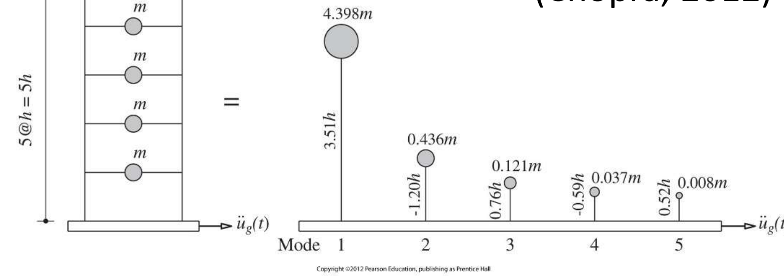
- Single Degree of Freedom (SDOF)

$$\omega_n = \sqrt{\frac{k}{m}} \quad \text{lumped}$$

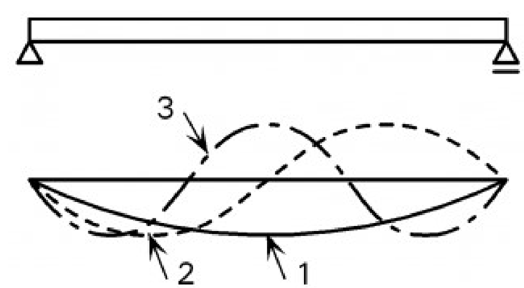
- Multiple Degree of Freedom (MDOF)
  - Mass, stiffness, and damping matrices
  - Strength of mode represented by effective modal mass and modal height (popsicles)
- Continuous

$$\omega_n = \frac{\pi^2}{L^2}\sqrt{\frac{EI}{m}} \quad \text{distributed}$$



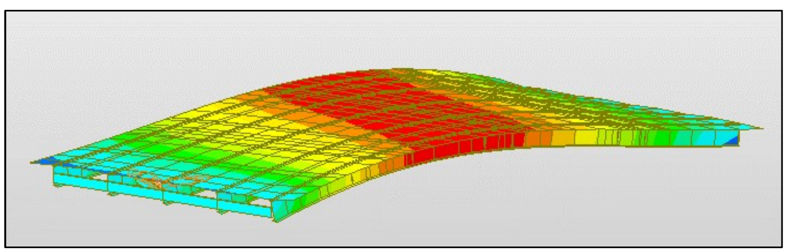


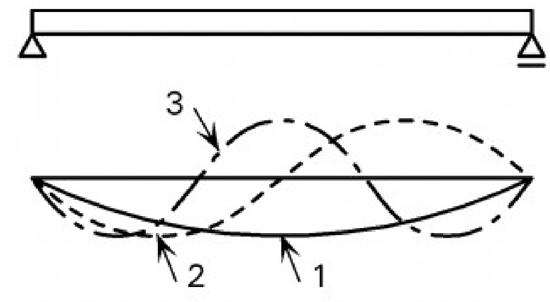
(Chopra, 2012)

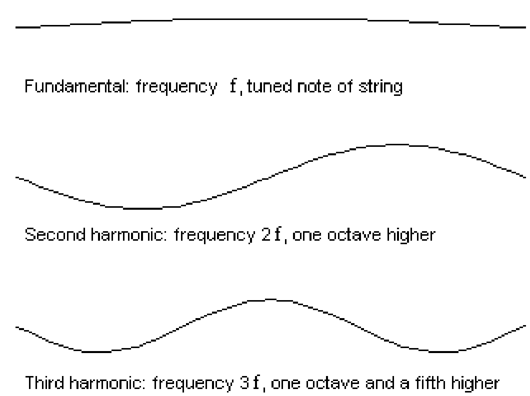


Mode Shapes and Frequencies

- Continuous beams are analogous to strings on an instrument
- Challenges of bridges
  - Distributed mass and stiffness
  - Non-structural components that contribute to stiffness
  - Soil-structure interaction
  - Limits of a model and appropriate boundary conditions
  - Vertical, lateral, torsional modes
  - Traffic can influence response measurement







https://plus.maths.org/content/why-violin-so-hard-play

Health Monitoring of Constructed Systems (Aktan et al 2005)

- History: dynamic testing a full-scale structures started in California in the early 1960's International Modal Analysis Conference (IMAC) since 1982
- Many methods are available and many have been proven successful
- Specific research in excitation, sensing, post-processing
- There is consensus that SHM can support performance-based design and asset management goals
- "The dynamic test of a constructed system should therefore be executed with a careful evaluation of observability, repeatability and the system of interacting elements of the engineered structure, the nature and the human."

A System Identification Problem

INPUT
- Non-stationary
- Echoes/Reflections
- Bandwidth
- Directionality
- Select Harmonics
- Interference/Noise

SYSTEM
- Non-stationarity due to changes in environment
- Nonlinearity
- Incomplete free body /Appendage tests
- Lack of observability due to insufficient sensor density
- Scale-induced complexity

OUTPUT
- Asynchronous
- Filters
- Sensor calibration
- Noise & bias
- Spurious pulses
- Bandwidth
- Window length
- Frequency resolution

DATA PROCESSING
- Data quality measures
- Error identification/Error Cleaning
- Filtering, averaging, windowing
- Post-processing

MEASURED PROPERTIES
- Frequency band
- Modal order
- Spatial adequacy
- 3D vs. Idealized
- Separation
- Amplitude & phase
- Damping

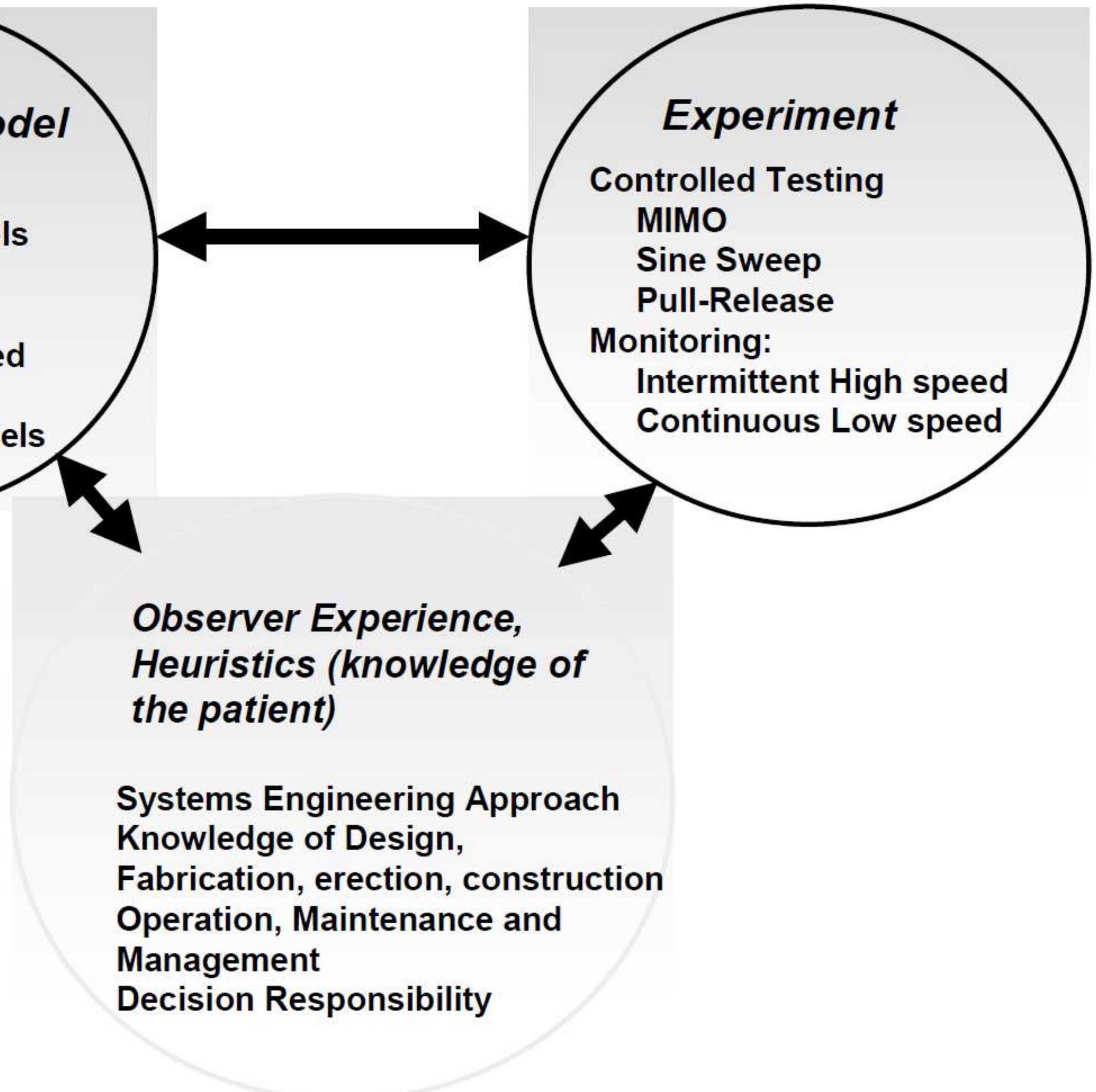
ANALYTICAL MODEL
- Completeness
- Material variability
- Geometry
- BC& CC
- Temporal/spatial Nonlinearity & Non-stationarity

PARAMETER ID
- Parameter grouping
- Sensitivity
- Bandwidth
- Modality
- Objective Function
- Optimization

VERIFICATION
- Modality
- Independence

TEST DESIGN
- Access
- Excitation
- Sensor density and modality
- Diagnose/Mitigate malfunctions

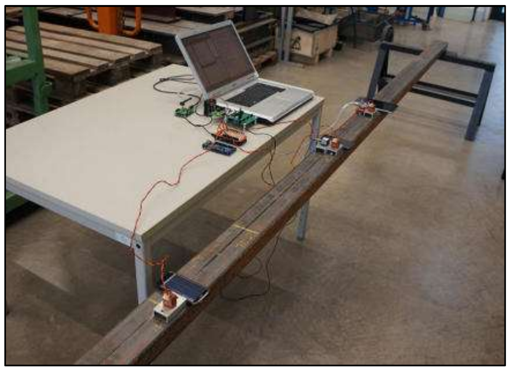
(Aktan et al 2005)



"The global relationship that should therefore govern the design of any field test to ensure success is illustrated."

(Aktan et al 2005)

Others Working with Mobile Devices



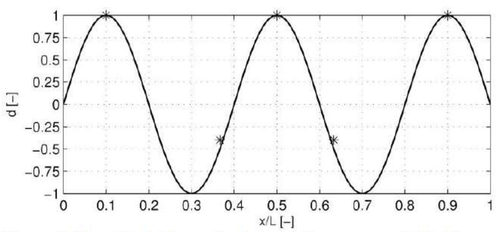
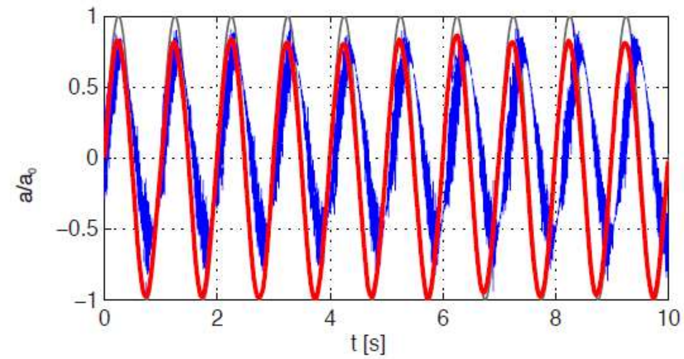
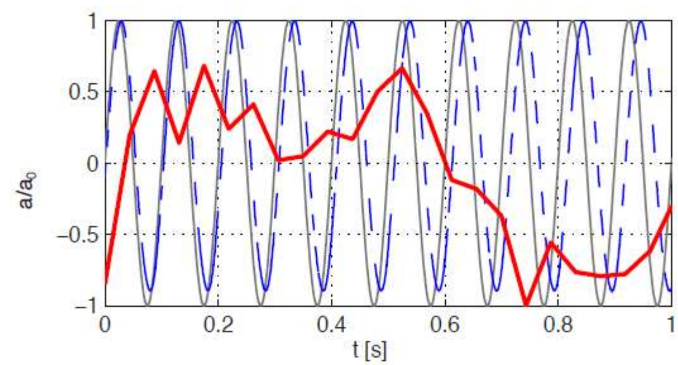


Figure 6. Identified 5th mode shape at frequency of 122 Hz.

- Morgenthal and Hallerman (2014) successfully identified the modal properties of a laboratory beam with an array of HTC Legend mobile phones
- Hopfner et al (2013) evaluated a series of mobile devices using a shake table including an iPhone 4 and indicated a degradation of the measurement above 8 Hz by an unidentified smartphone



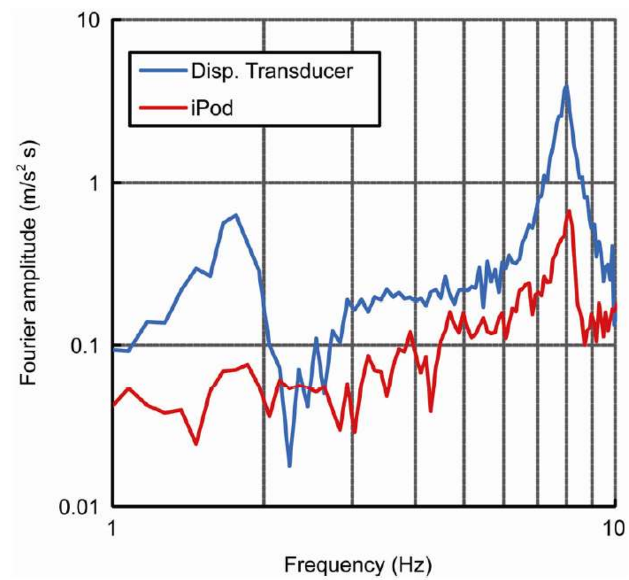
(a) $f = 1\,\mathrm{Hz}$, $a = 1\,\mathrm{m/s^2}$



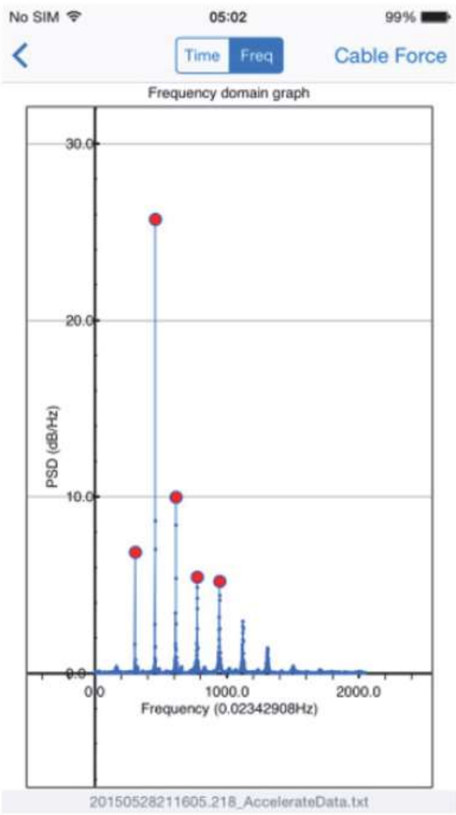
(b) $f = 10\,\mathrm{Hz}$, $a = 2\,\mathrm{m/s^2}$

Others Working with iPods

- Naoki et al (2015) tested light poles; compared iPod to conventional accelerometer and laser Doppler displacement transducer with good agreement
- Found stability of frequency over days
- Found reduced frequency over years
- Unable to identify reason for reduced frequency, but likely soil-structure related



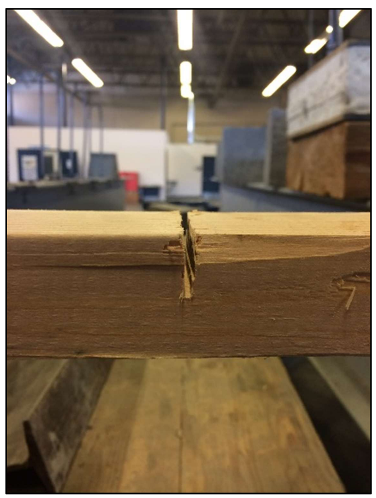
Others Working with iPods and Vision Sensing

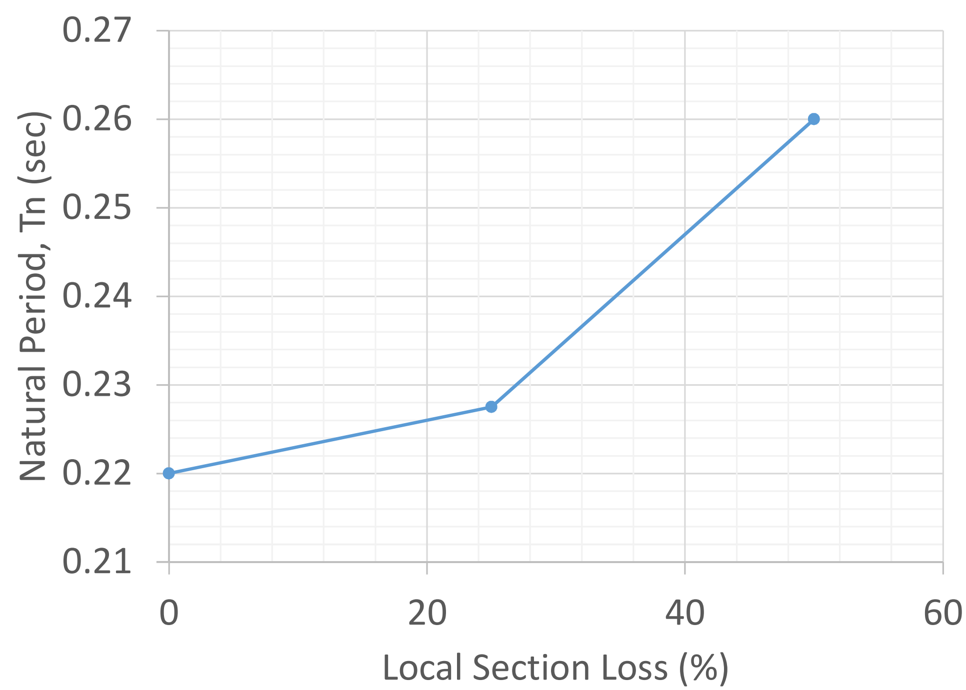


- Zhao et al (2016) developed an app (Orion-CC) for documenting SHM experiments with iOS device accelerometers and video
- Focus is on a quick evaluative method
- Bridge cable forces were measured with good accuracy
- Very similar to the research we are doing at Oregon Tech

A Simple Damage Detection Lab Module

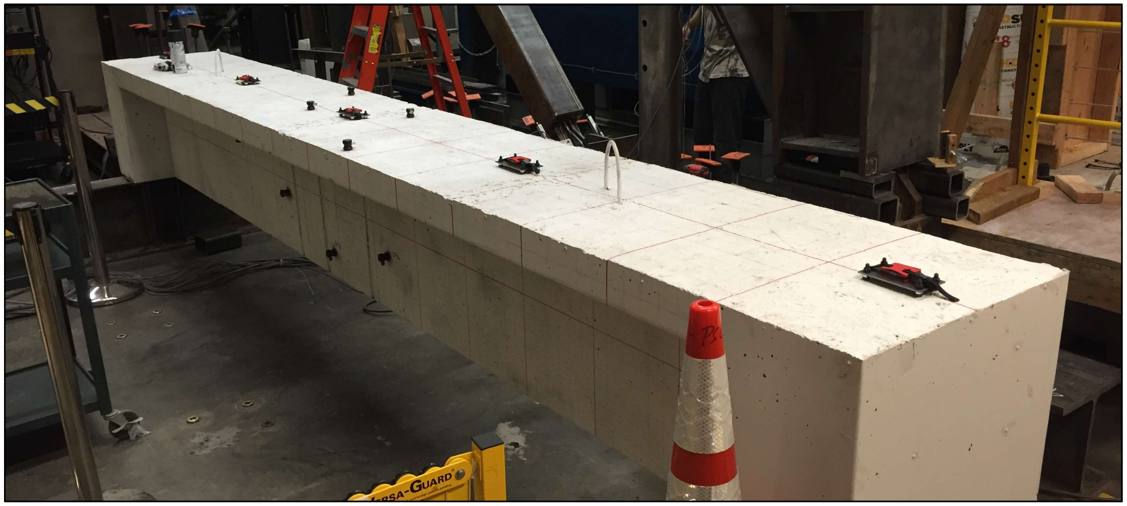
- Section loss inflicted near the support (25% and 50%)
- Change in natural period measured with iPod





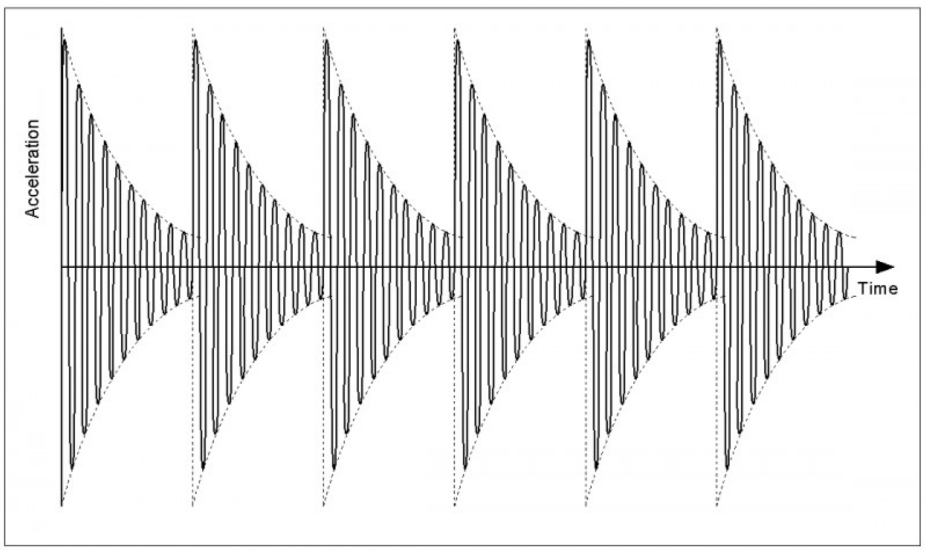
Concrete Beam Lab Testing

- Compared results of iPod measurements to those from an instrumented hammer
- Agreement in fundamental frequency



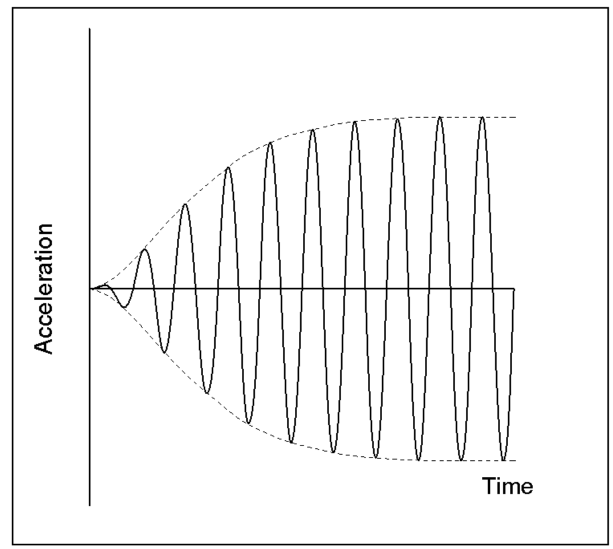
Methods of Excitation

Periodic Impact/Impulse



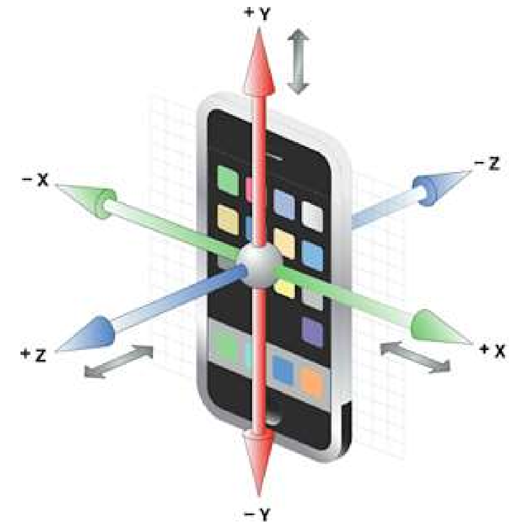
Jumping in Unison, Impact Hammer

Harmonically Forced



Shaker

Methods of Sensing

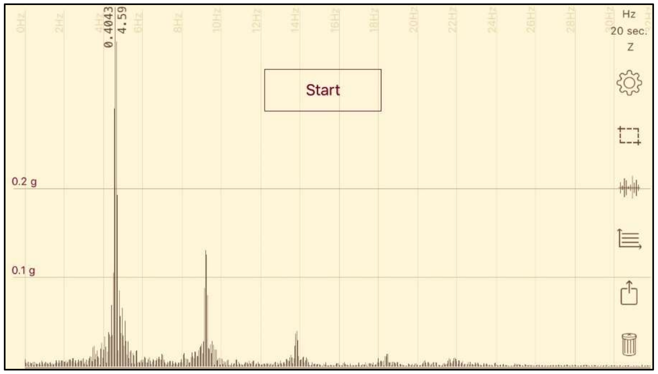


- Contact Sensing:
  - Conventional accelerometers
  - Mobile device accelerometers
  - Apps
    - Seismometer
    - Vibration Analysis
    - Others

- Non-Contact Sensing: Virtual Visual Sensors
  - Canon Rebel T3i shooting 60 fps at 1280x720
  - Precursors: Machine vision, photogrammetry,
  - Other methods: blurred image

http://usefulmobileapps.com/en/vibration-spectrum-analysis.php

iOS Apps Available

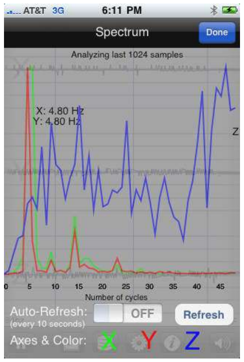


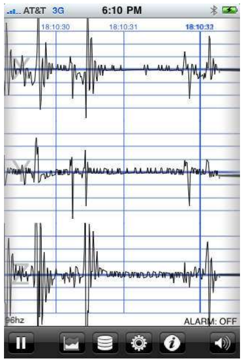
Current favorites:

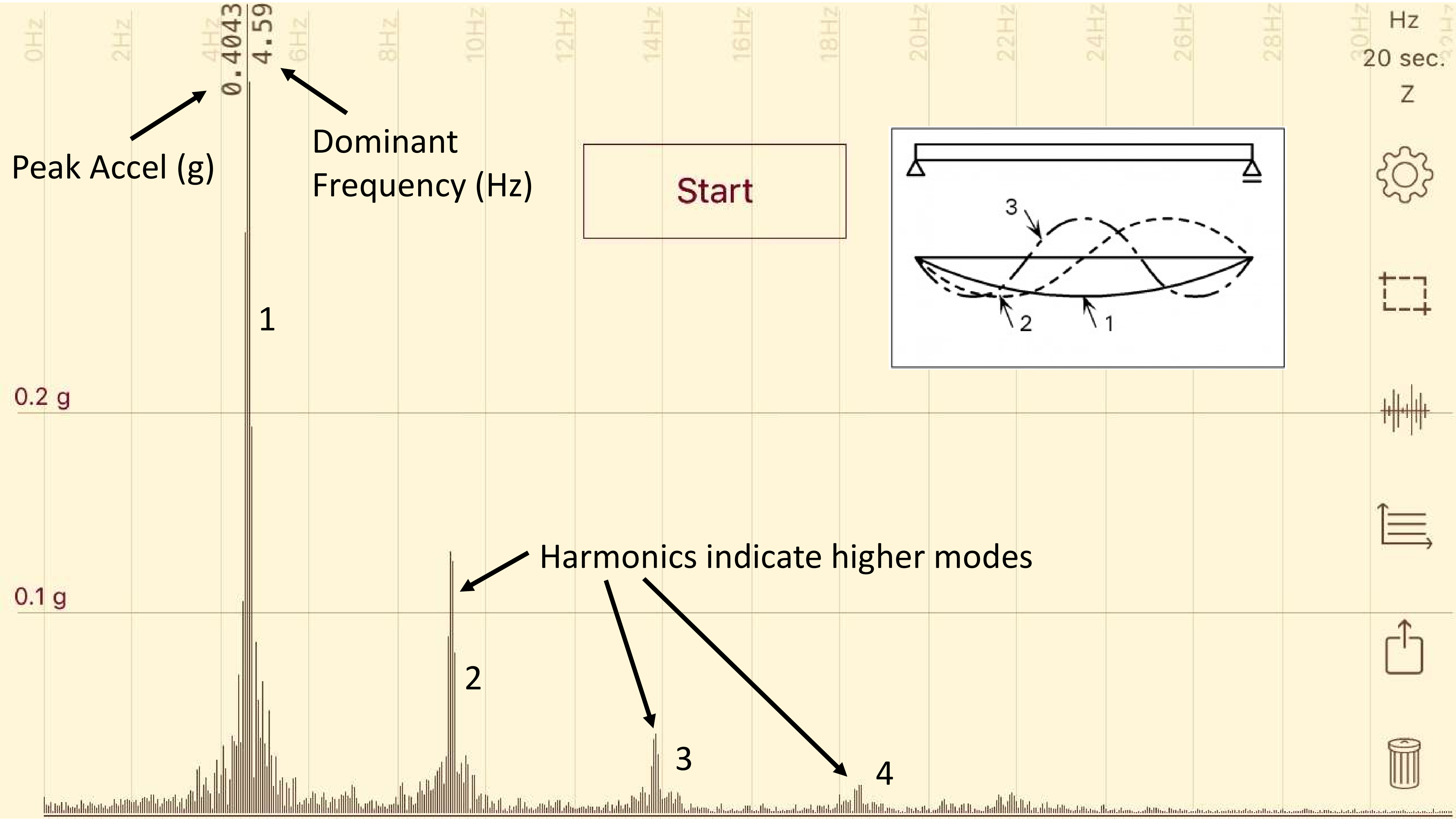
- Vibration Analysis
  - Frequency spectrum with amplitude
  - Email export of both time history and frequency spectrum
  - Screen capture
  - Adjustable units and FFT window (5, 10, 20 seconds)
- Orion-CC – document location and response with frequency spectrum

Many now out of date and with limited compatibility with current iOS:

- Seismometer – UDP broadcast of data, 2 minutes of data collection
- iSeismometer – Frequency spectrum, email time history
- Sensor Stream – UDP broadcast of data
- Accelerometer
- Sensor Kinetics
- Many more seem to appear daily…



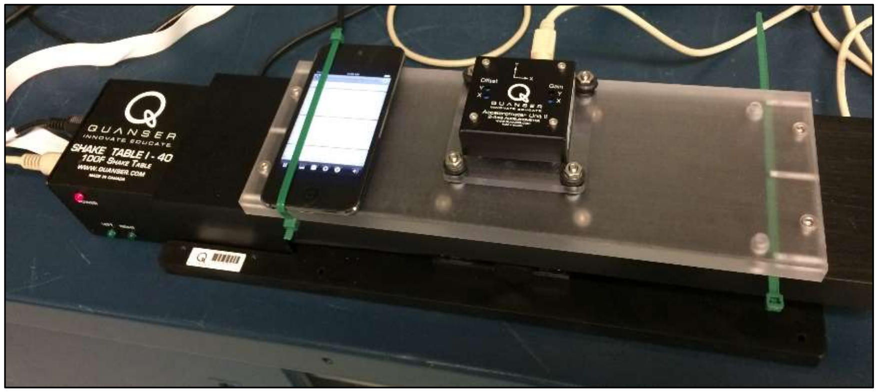


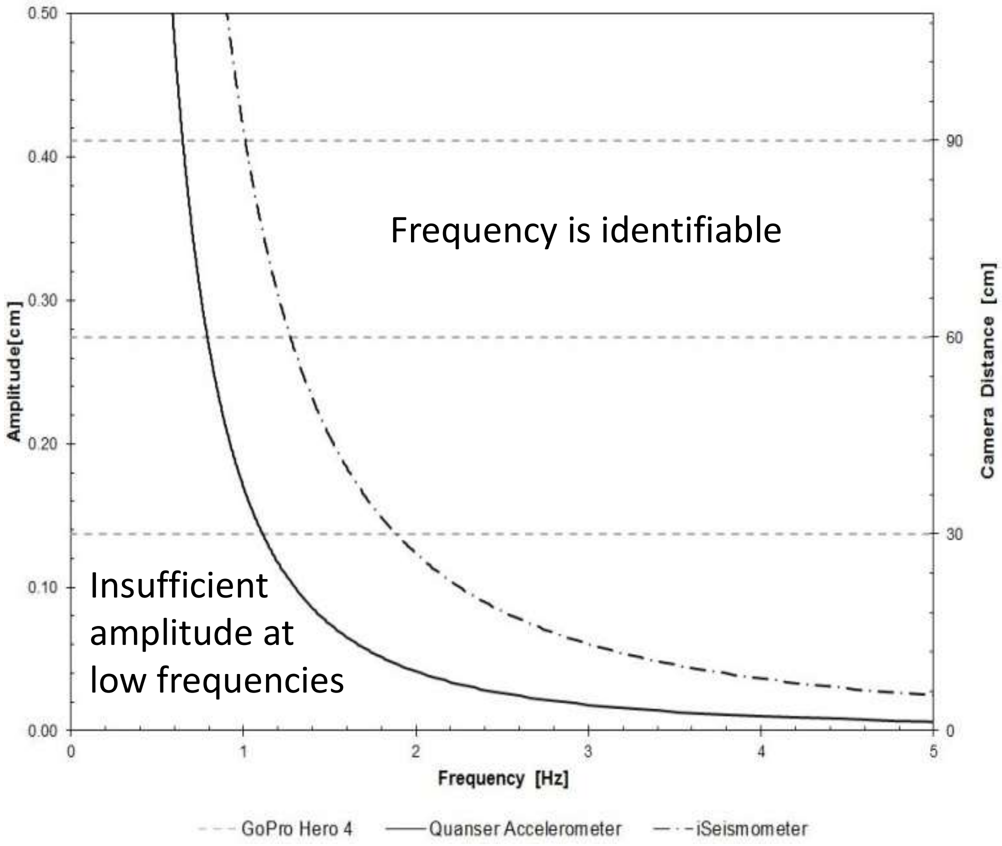


0Hz
2Hz
4Hz
6Hz
8Hz
10Hz
12Hz
14Hz
16Hz
18Hz
20Hz
22Hz
24Hz
26Hz
28Hz
30Hz
0.4043
4.59
Hz
20 sec.
Z
Peak Accel (g)
Dominant
Frequency (Hz)
Start
0.2 g
0.1 g
1
2
3
4
Harmonics indicate higher modes

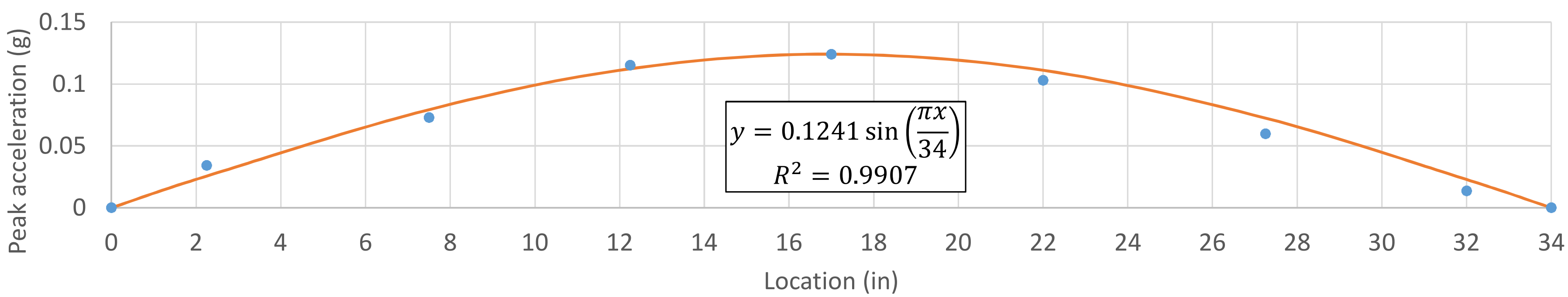
Experiments to Confirm Frequency Identification: Shake Table Testing

- Frequency identified within 0.2 Hz
- Quanser accelerometer
- iPod accelerometer
- VVS is frequency-independent; amplitude depends on camera distance and video resolution



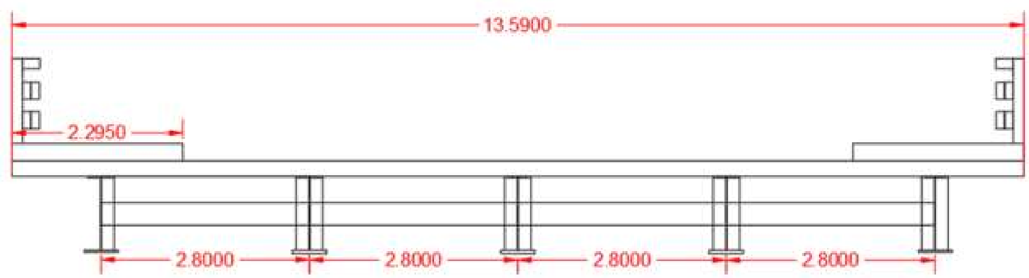


Experiments to Confirm Mode Shape Identification: A Simply-Supported Yardstick



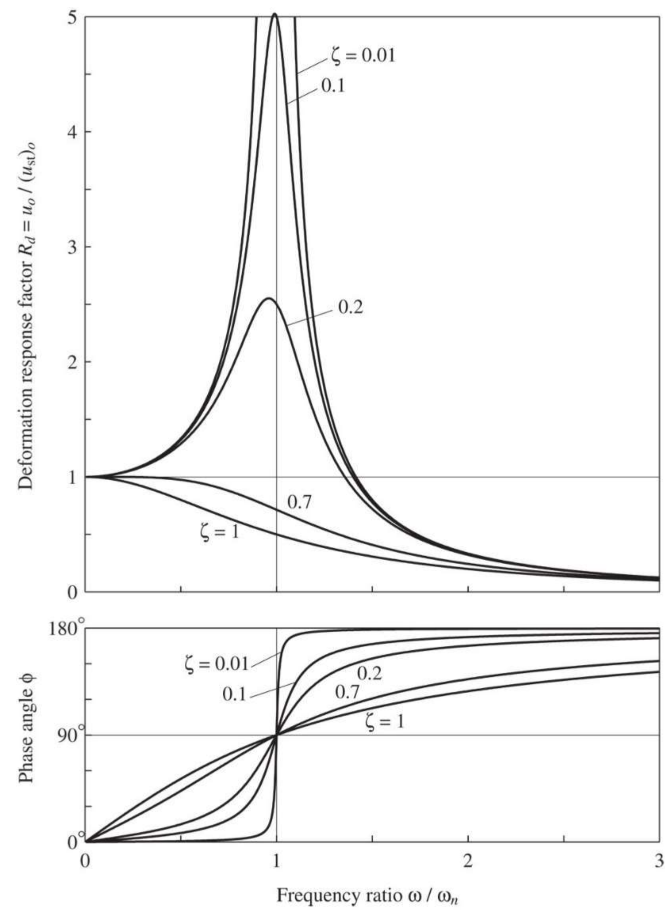
Field Studies

- Eberlein St. Bridge over the A-Canal
- 28.7-meter span
- 30-degree skew
- Composite steel girders with variable flange thickenss

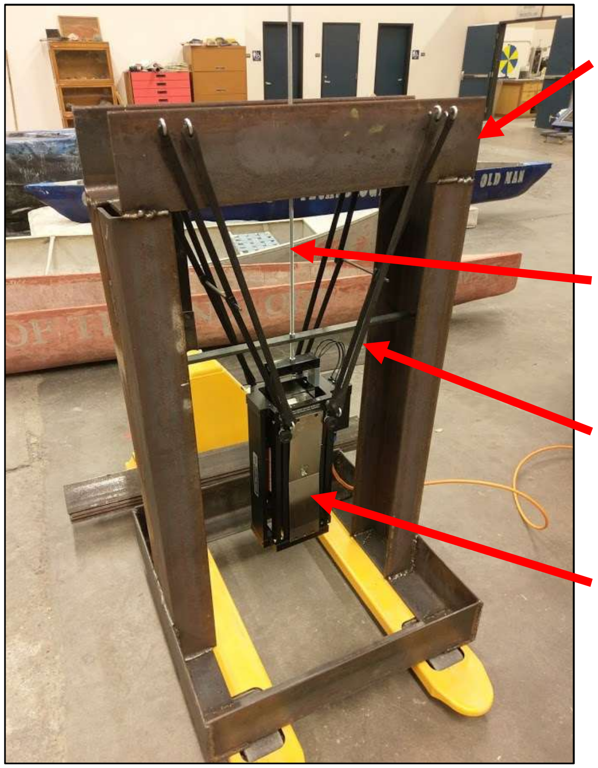


Forced Vibration

- Given frequencies estimated based on bridge response to ambient traffic
- Forcing at modal frequencies should produce the maximum amplitude of response by dynamic amplification
- Amplitude of response at resonance is related to damping of the structure



Shaker Frame



- ~300-lb frame ensures that shaker forces are transferred directly into the structure without bolting or other attachment
- Dynamic force is transferred through the tie rod connected to the armature
- Equilibrium position is maintained by array of bungee cords
- 78-lb shaker body

Shaker Limits

- Shaker has the capability of producing a very precise sinusoidal forcing at a desired frequency
- 30-lb max dynamic force between 1 and 20 Hz
- Maximum practical force was likely 20 lb

CHARACTERISTICS AND PERFORMANCE PARAMETERS

Frequency Range . . . . 0 to 200 Hz

Force Rating 113, 113-LZ (continuous)

dc to 0.1 Hz . . . . 21 lb, 94 N

Above 0.1 Hz . . . . 30 lb, 133 N peak

Above 20 Hz . . . . Refer to figure 3-7

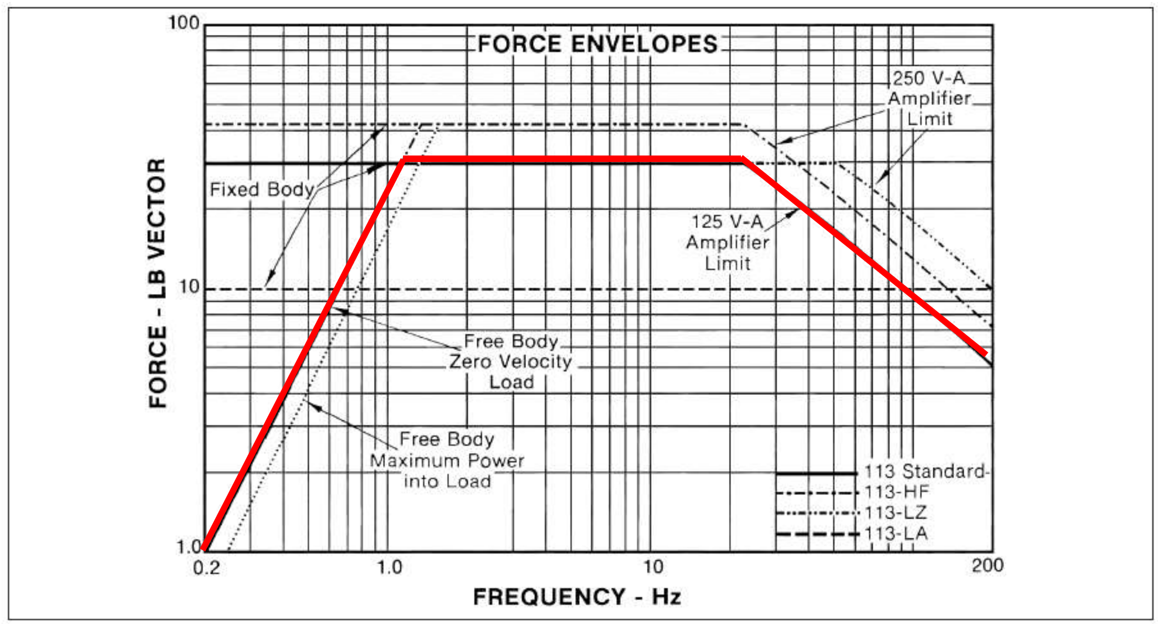


Figure 3-7 Force envelope for Model 113 Shaker in the fixed and free body modes

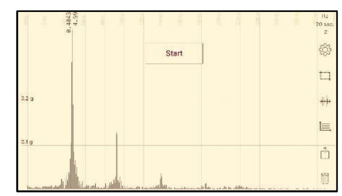
Laptop with control software: function generator

Active control board

Amplifier

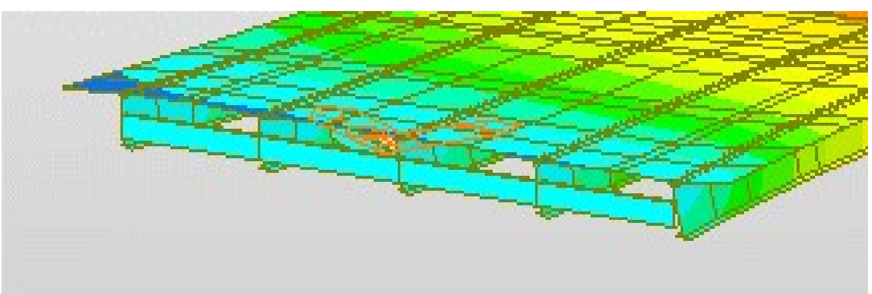
Linear shaker

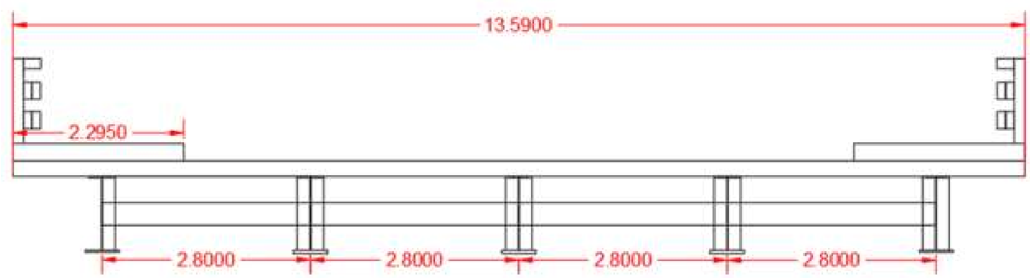
iPod with real-time frequency spectrum



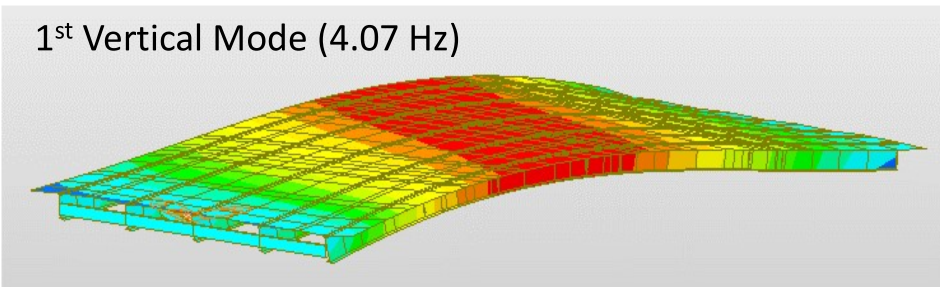
A Priori Model - Adjusted

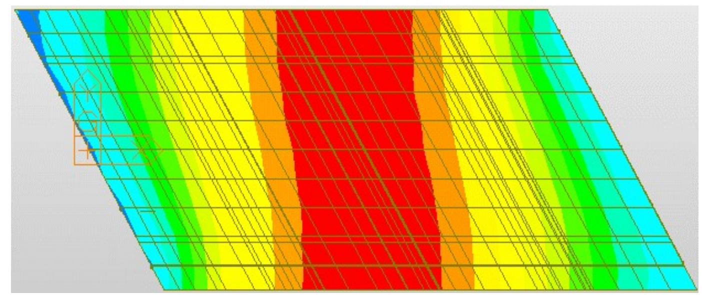
- A detailed finite element analysis using plate elements
- Results of a modal analysis: mode shapes and frequencies
- Identifying antinodes – good locations for both excitation and response measurement

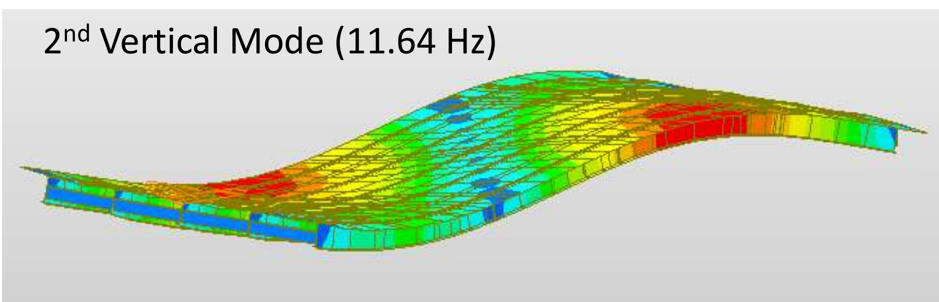


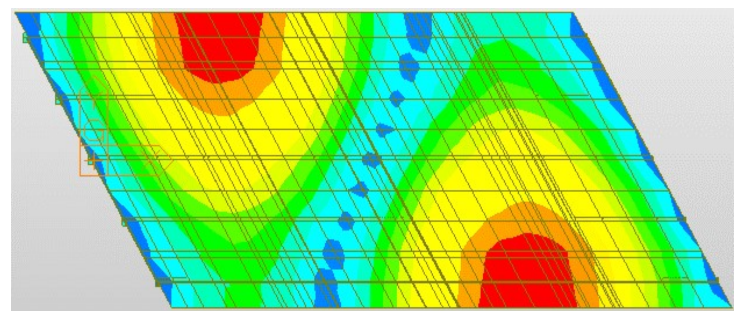


Numerical Modeling – Modal Analysis Vertical Modes

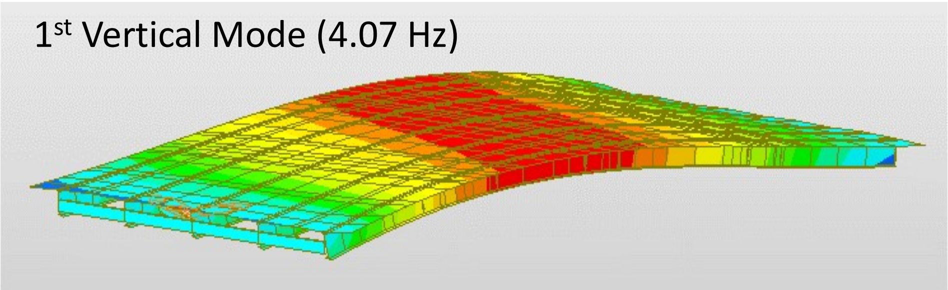


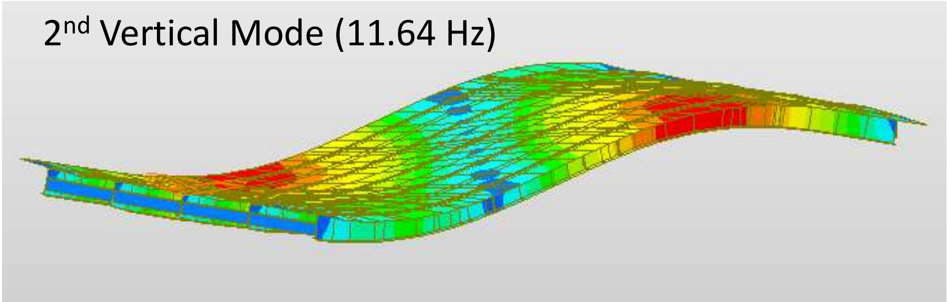


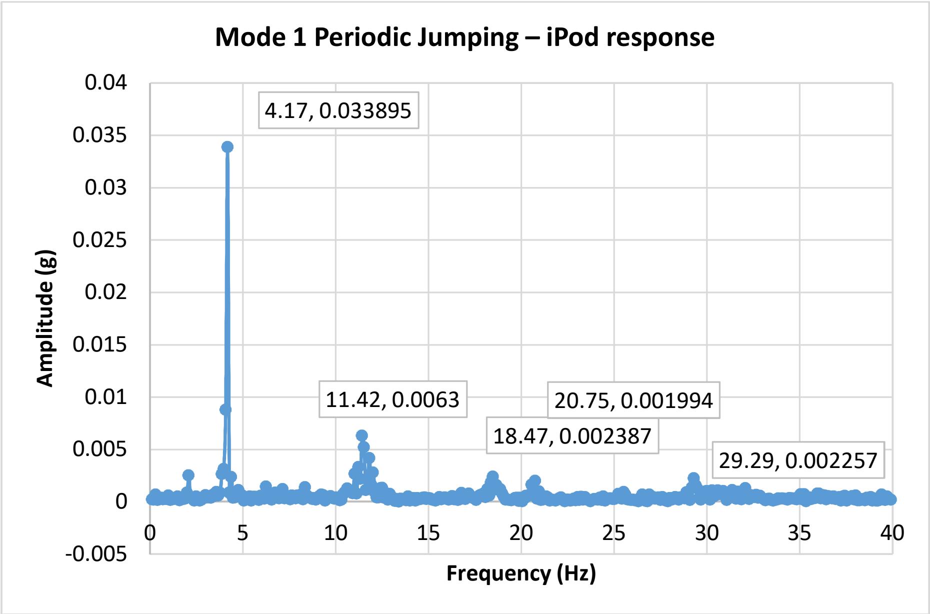




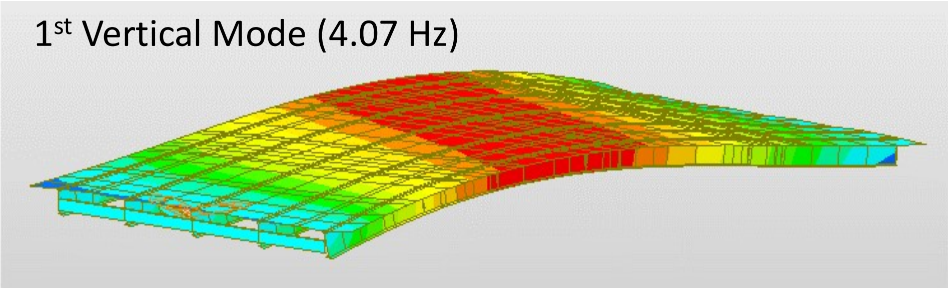
Numerical Modeling – Modal Analysis
Vertical Modes vs iPod Measurements

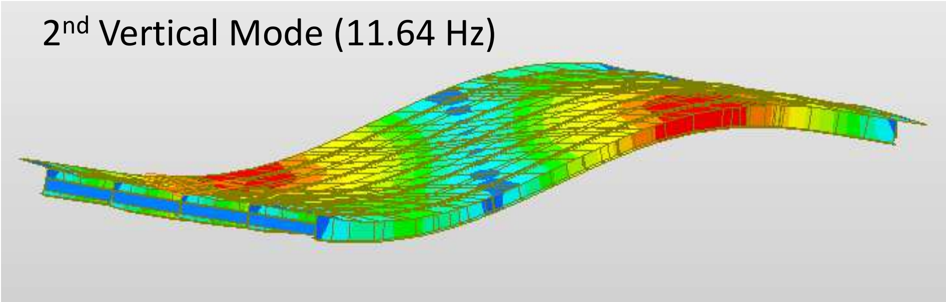


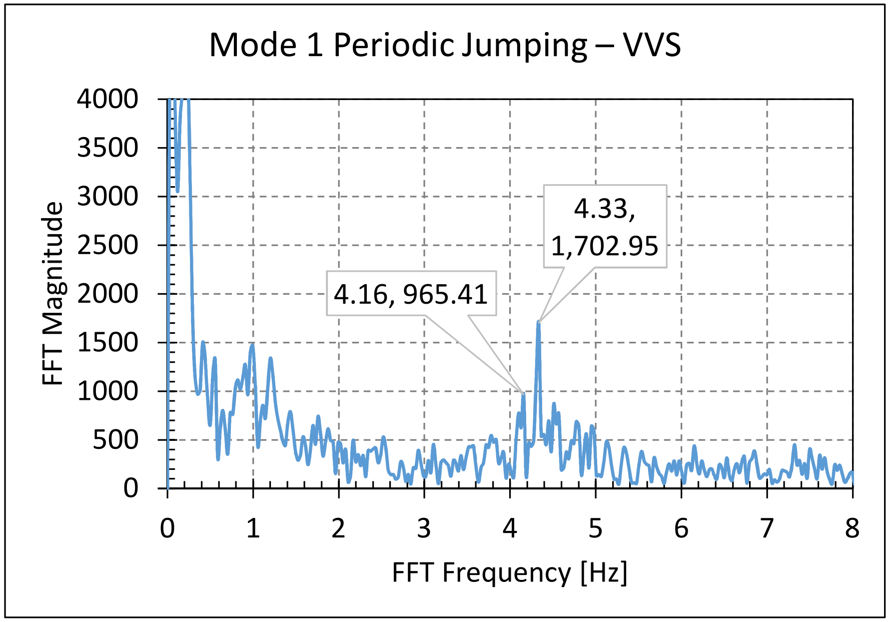




Numerical Modeling – Modal Analysis
Vertical Modes vs VVS Measurements

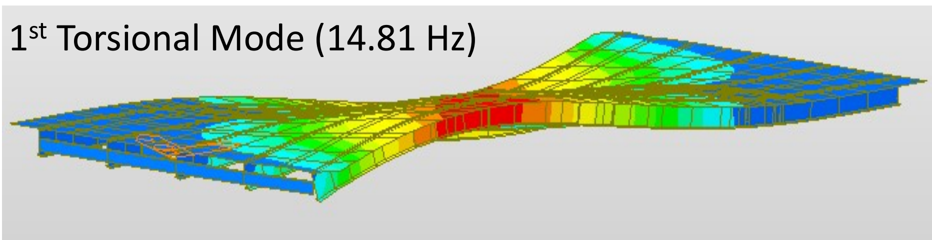


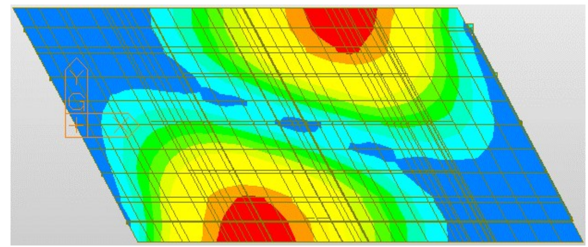




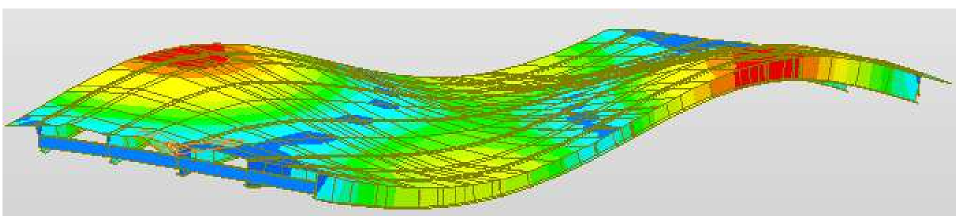
Numerical Modeling – Modal Analysis Torsional Modes

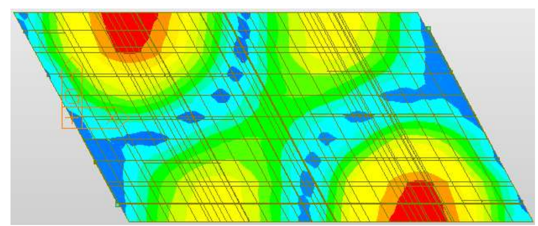
1st Torsional Mode (14.81 Hz)



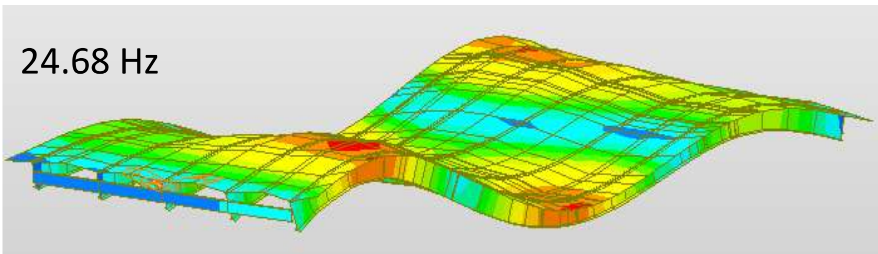


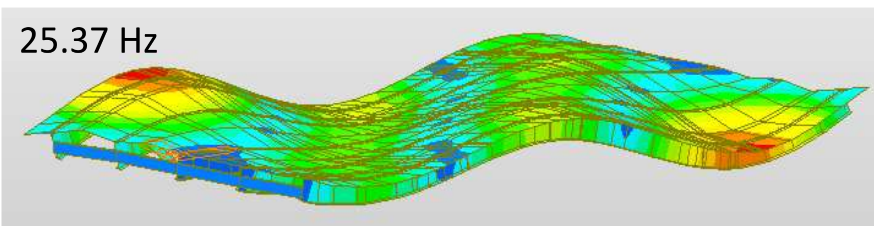
2nd Torsional Mode (17.25 Hz)

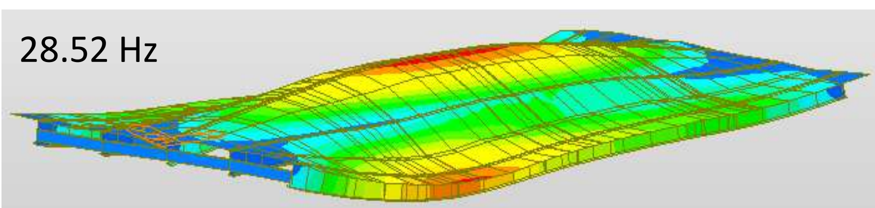


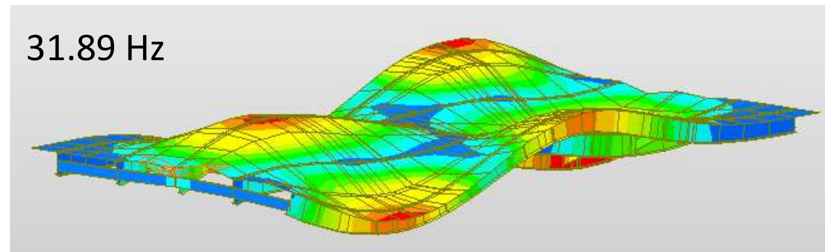


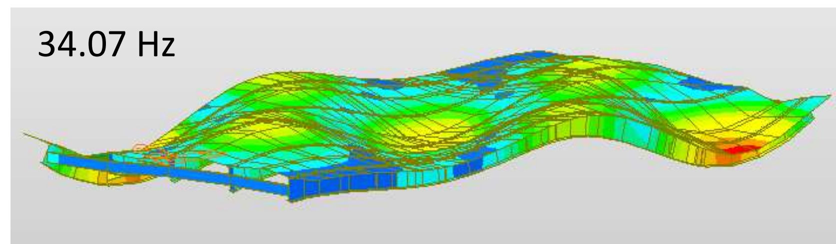
Numerical Modeling – Modal Analysis
Higher Modes



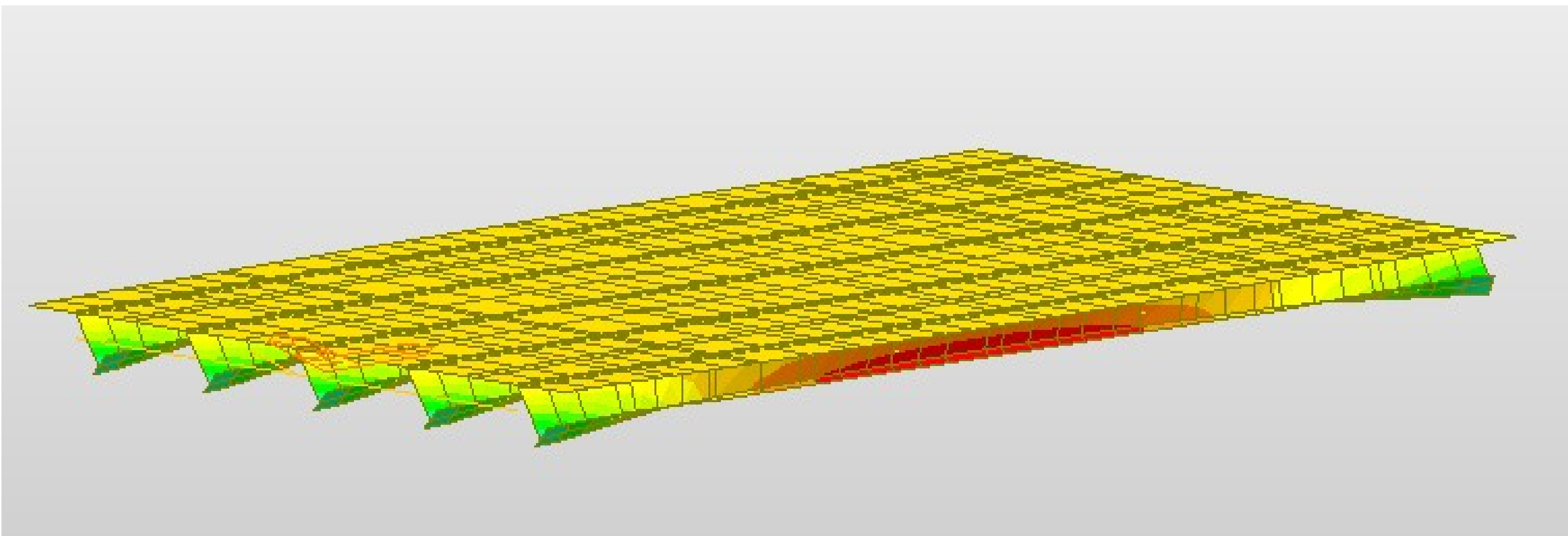








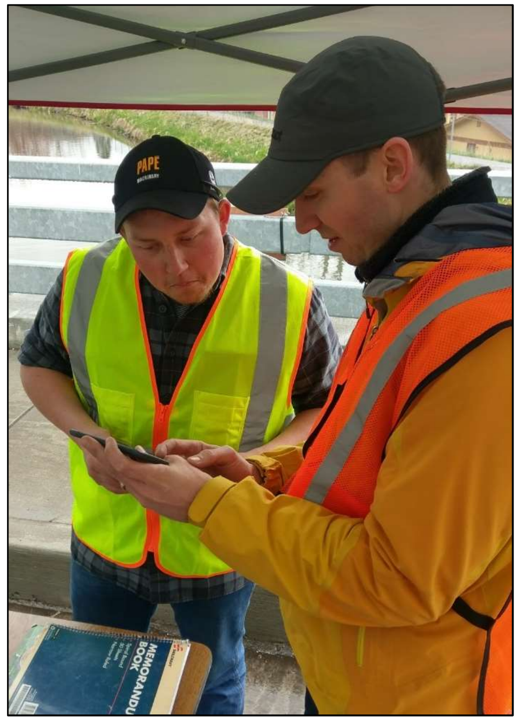
Model Validation:
Lateral Torsional Buckling Modes?



Future Work

- Streamline procedure for implementation by bridge inspection crew
- More field work in summer 2017 to validate results and field test procedure
- Further review of literature and tools available

Thank you!



Questions?

References

- Chopra, Anil K. *Dynamics of structures 4th Ed*. Pearson, 2012.
- Zhao, Xuefeng, Kwang Ri, Ruicong Han, Yan Yu, Mingchu Li, and Jinping Ou. "Experimental Research on Quick Structural Health Monitoring Technique for Bridges Using Smartphone." *Advances in Materials Science and Engineering* 2016 (2016).
- Höpfner, Hagen, Guido Morgenthal, Maximilian Schirmer, Marcel Naujoks, and Christoph Halang. "On measuring mechanical oscillations using smartphone sensors: Possibilities and limitation." *ACM SIGMOBILE Mobile Computing and Communications Review* 17, no. 4 (2013): 29-41.
- Morgenthal, Guido, and Hagen Höpfner. "The application of smartphones to measuring transient structural displacements." *Journal of Civil Structural Health Monitoring* 2, no. 3-4 (2012): 149-161.
- Webb, G. T., P. J. Vardanega, and C. R. Middleton. "Categories of SHM deployments: technologies and capabilities." *Journal of Bridge Engineering* 20, no. 11 (2014): 04014118.
- Salawu, Olusegun S., and Clive Williams. "Bridge assessment using forced-vibration testing." *Journal of structural engineering* 121, no. 2 (1995): 161-173.
- Aktan, Ahmet Emin, S. K. Ciloglu, K. A. Grimmelsman, Q. Pan, and F. N. Catbas. "Opportunities and challenges in health monitoring of constructed systems by modal analysis." In *Proceedings of the International Conference on Experimental Vibration Analysis for Civil Engineering Structures*, pp. 11-34. 2005.