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Passive monitoring of actual buildings

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Motivation

Structural Health Monitoring

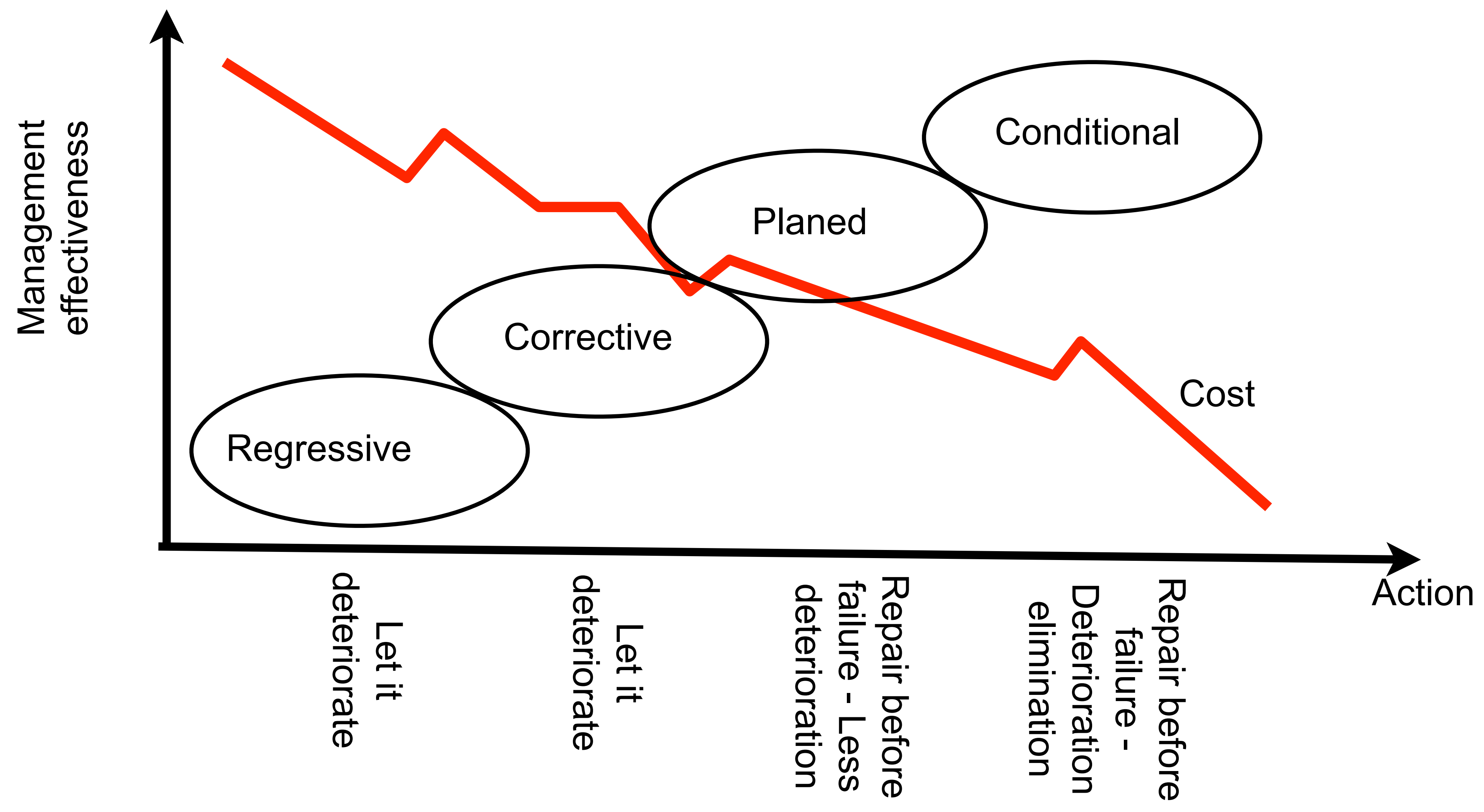
Continuous aging and subsequent structural deterioration of a large number of existing structures

Risk of collapse of the administrative building center in Nice "certainly unpredictable in time or in terms of probabilities, but there exists a real emergency to evacuate

International Energy Agency (IEA 2001) : “in the absence of changes in policy on nuclear energy, the lifespan of plants is the most determining factor for nuclear power for the next decade".

Motivation

Condition Based Maintenance

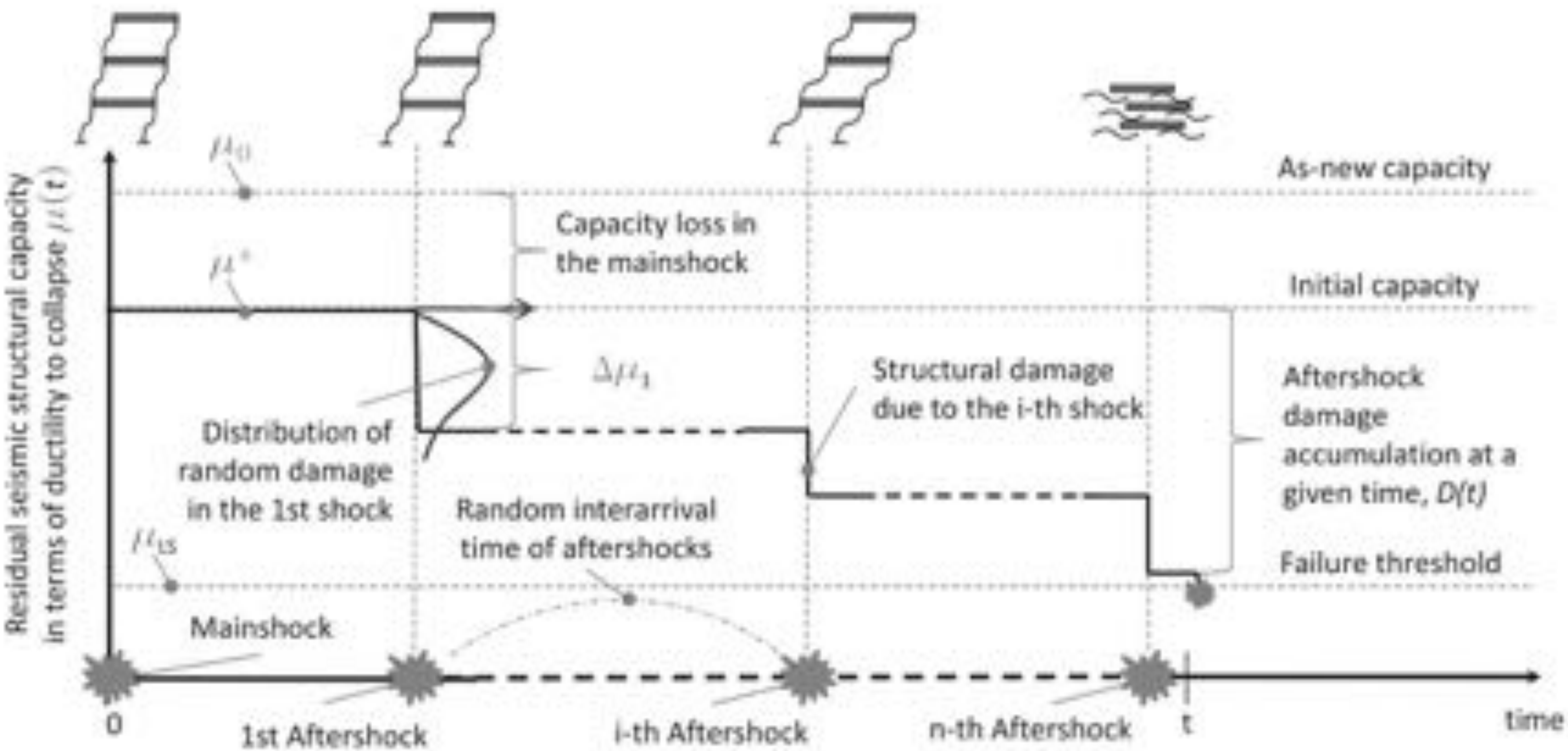


To prevent the total interruption of production activity by anticipating the renovation operations engaged on the basis of the observed structural condition

Motivation

Seismic crisis management

Progressive damage and change of condition of structures during aftershock sequences



Iervolino et al., Earthq. Spectra, 2014

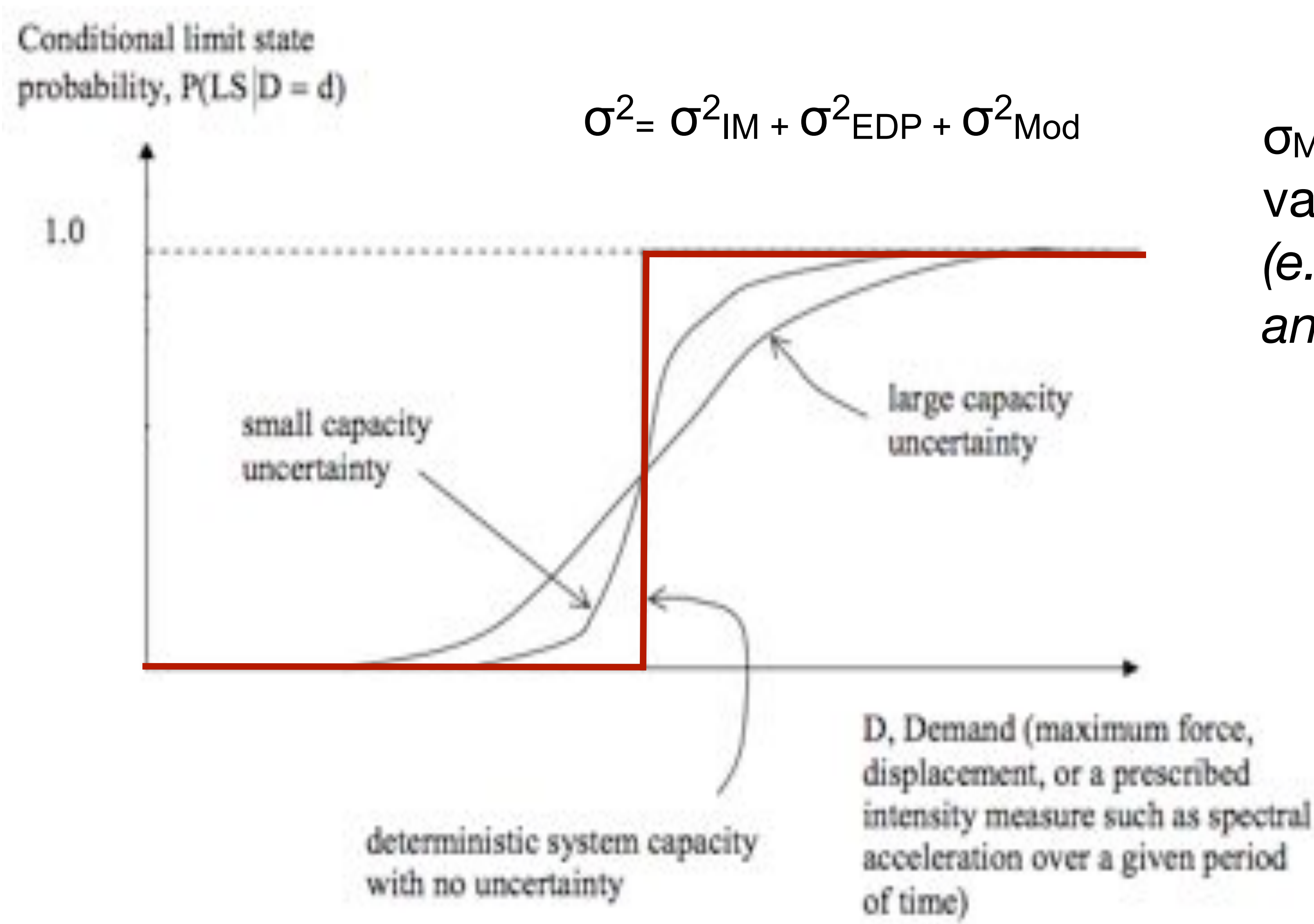
Motivation

Design-related uncertainties in Damage and risk prediction

Motivation

$$P(d > ds)[A] = \frac{1}{2}\left(1 + erf\left(\frac{\ln(A) - \ln(\mu)}{\sigma\sqrt{2}}\right)\right)$$

$\sigma^2 = \sigma^2_{IM} + \sigma^2_{EDP} + \sigma^2_{Mod}$



σ_{Mod} = Building-to-building variability within a building class *(e.g variability of building properties and design for a given typology)*

- Default of design
- Aging or damage changing the model
- Boundary condition
- Non linear response

Presentation Outline

Part 1: Motivation

Part 2: Structural Dynamics

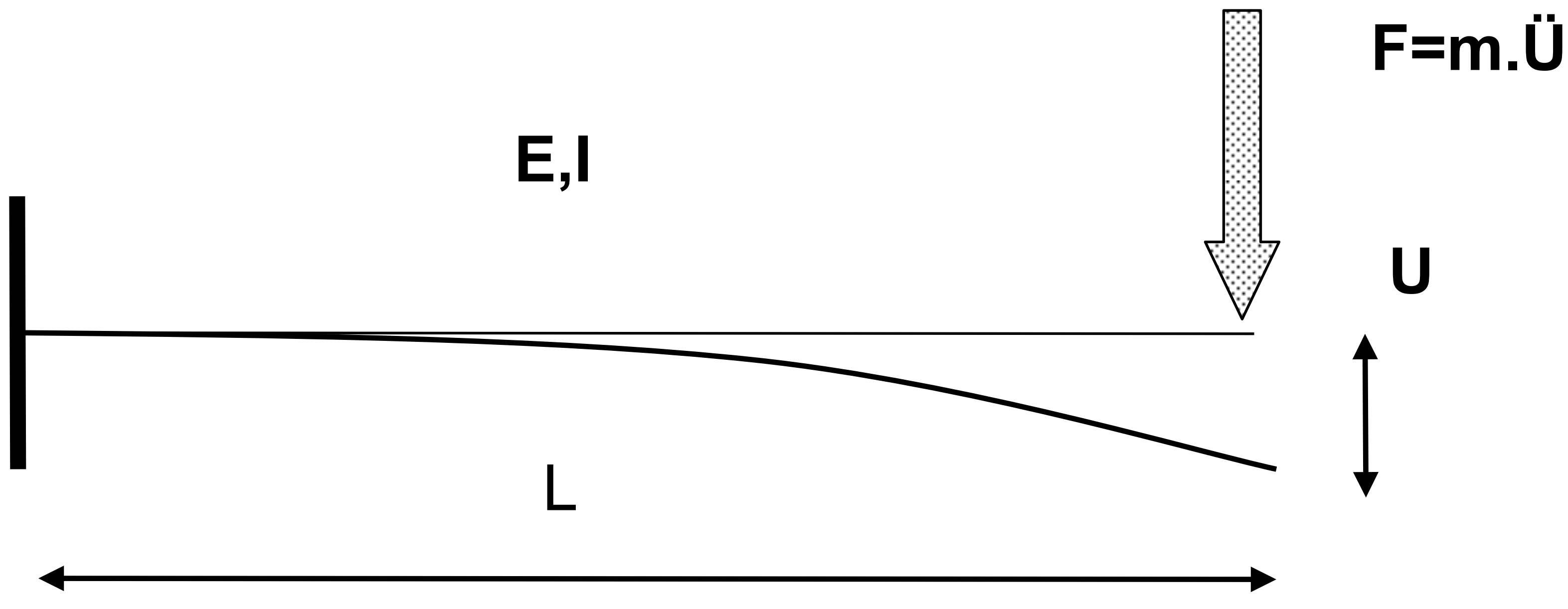
Part 3: Experimental assessment of dynamic parameters

Part 4: Passive imaging of buildings

Part 5: Non-linear seismic response of buildings

Part 6: Natural wandering of the building response

Structural dynamics



F [N] Force
U [m] Displacement
k [N/m] Stiffness
Ü [m/s^2] Acceleration

$F = k.U$

$k = 3.E.I/L^3$ for fixed base model

E= Young modulus - *Material*

I= Inertia momentum - *Geometry/shear resistance*

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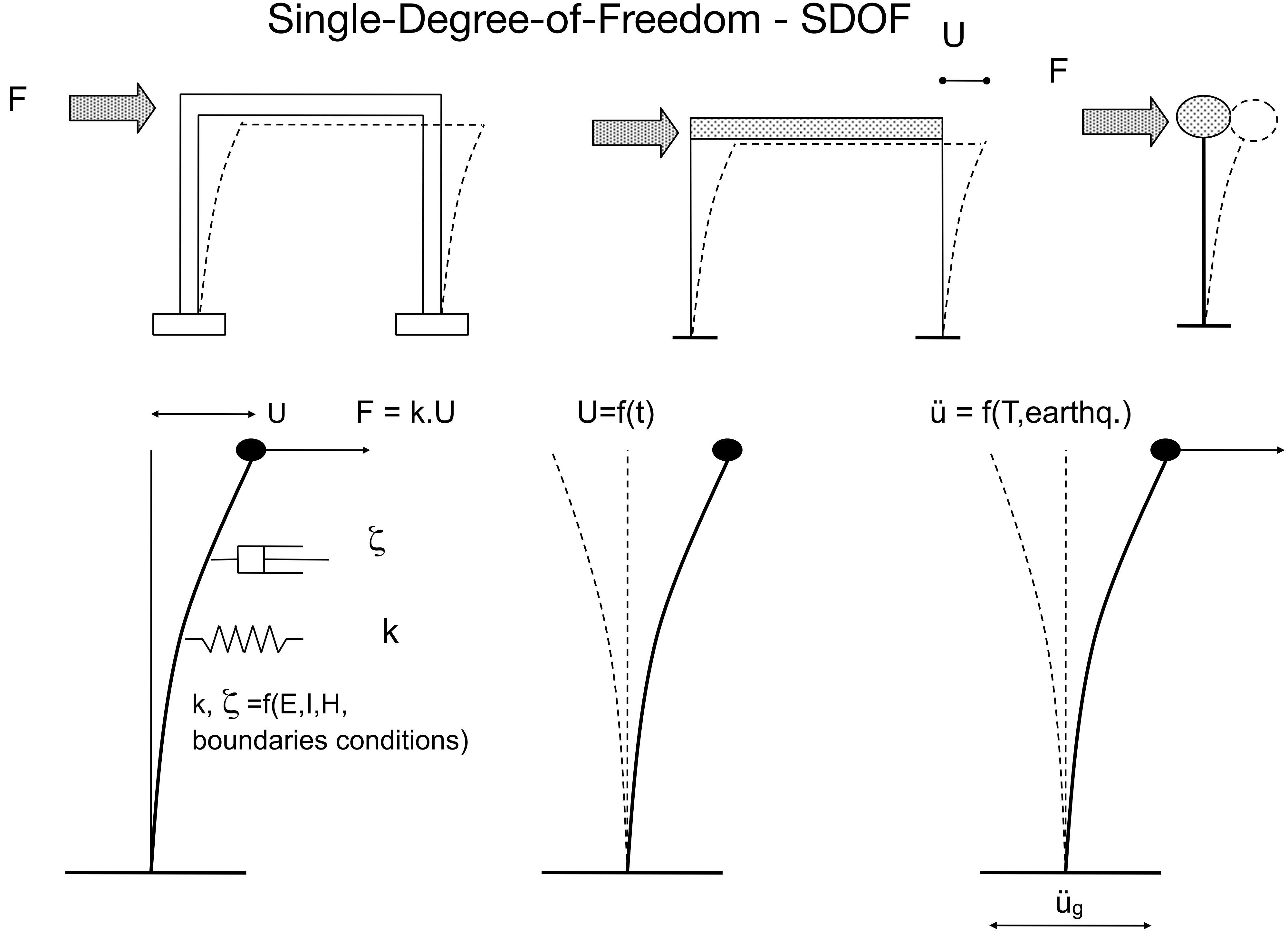
Structural dynamics

Single-Degree-of-Freedom - SDOF

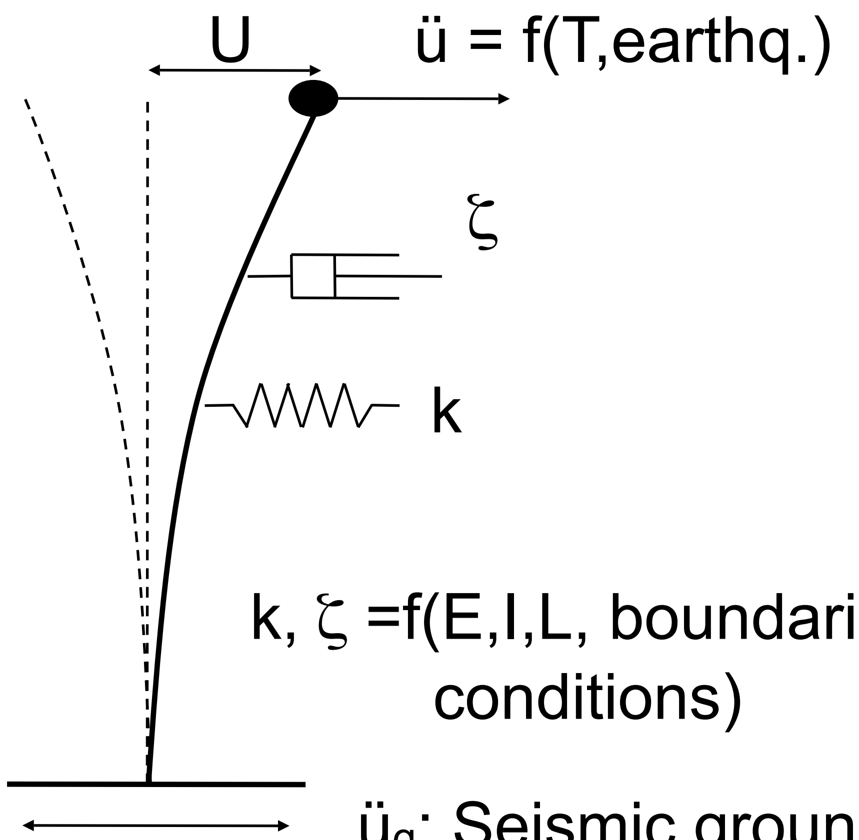


Static

Dynamic
Free-oscillations

Dynamic
Forced Oscillations

Structural dynamics



k, ζ =f(E,I,L, boundaries conditions)

$\ddot{u}_g$: Seismic ground motion (# seismic regulation)

Equation of motion - SDOF

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g$$

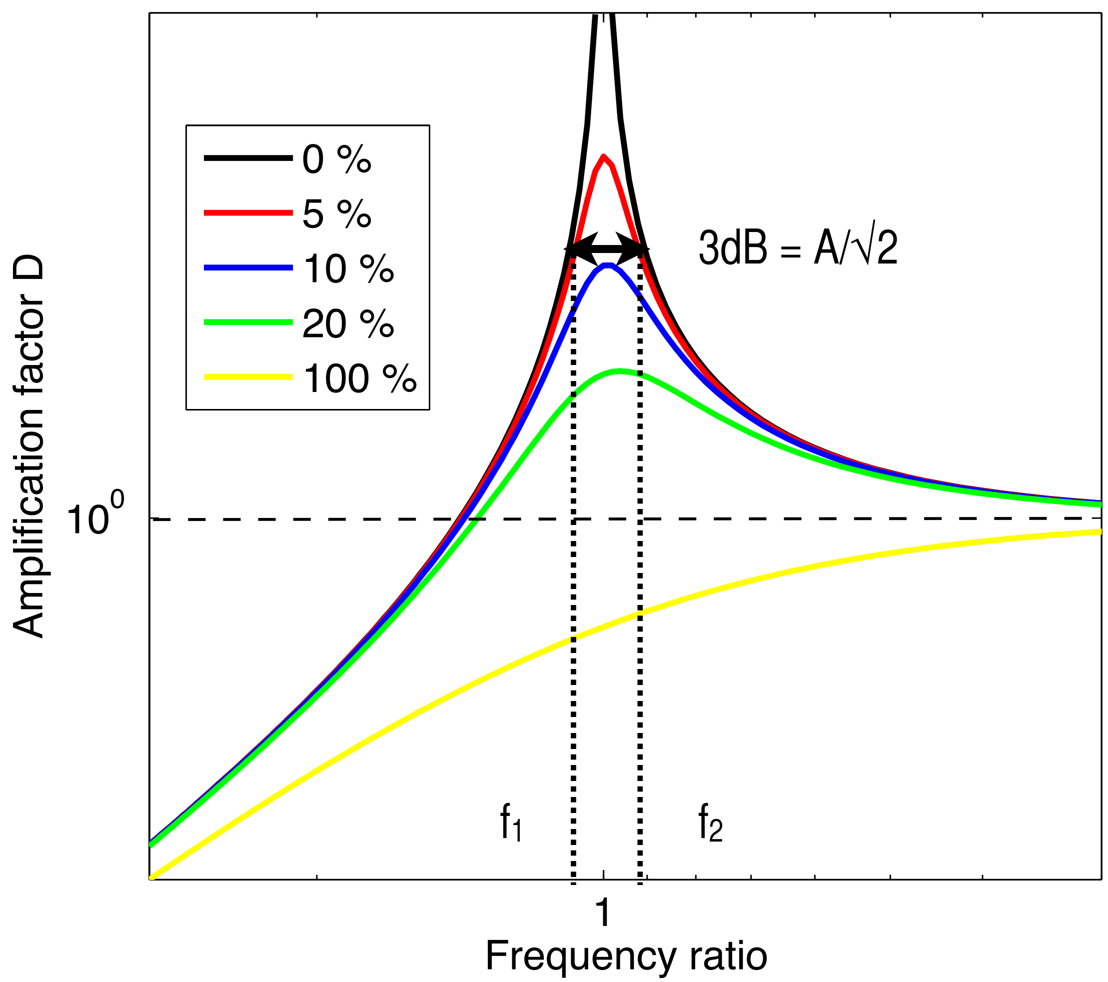
$$\ddot{u}(t) + 2\zeta\omega_o\dot{u}(t) + \omega_o^2 u(t) = -\ddot{u}_g(t)$$

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$ natural frequency

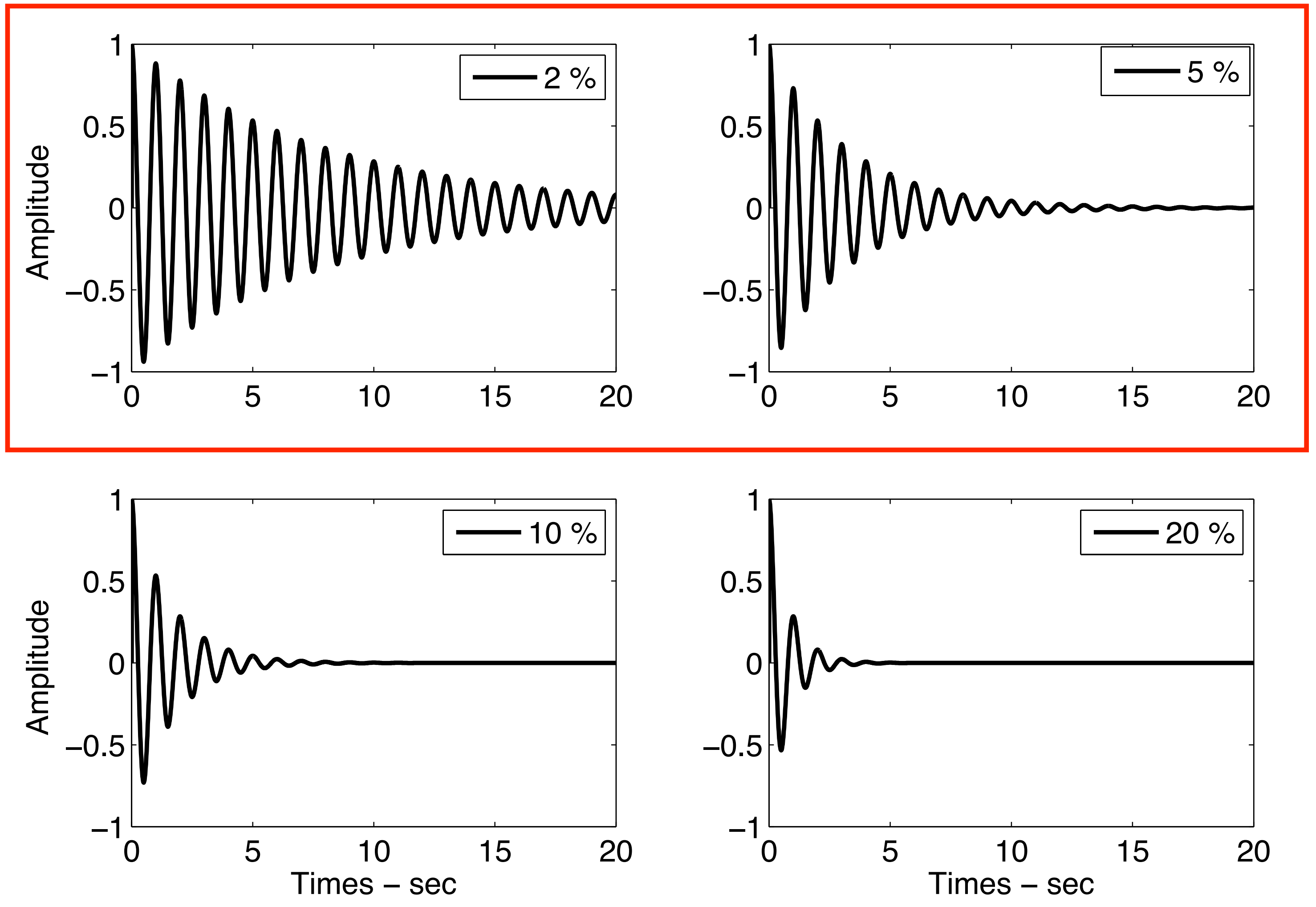
$$\zeta_o = \frac{c}{2\omega_o m} = \frac{c}{2\sqrt{km}}$$ % of critical damping

Structural dynamics

Frequency response of SDOF
(with f_o const., varying ζ_o)

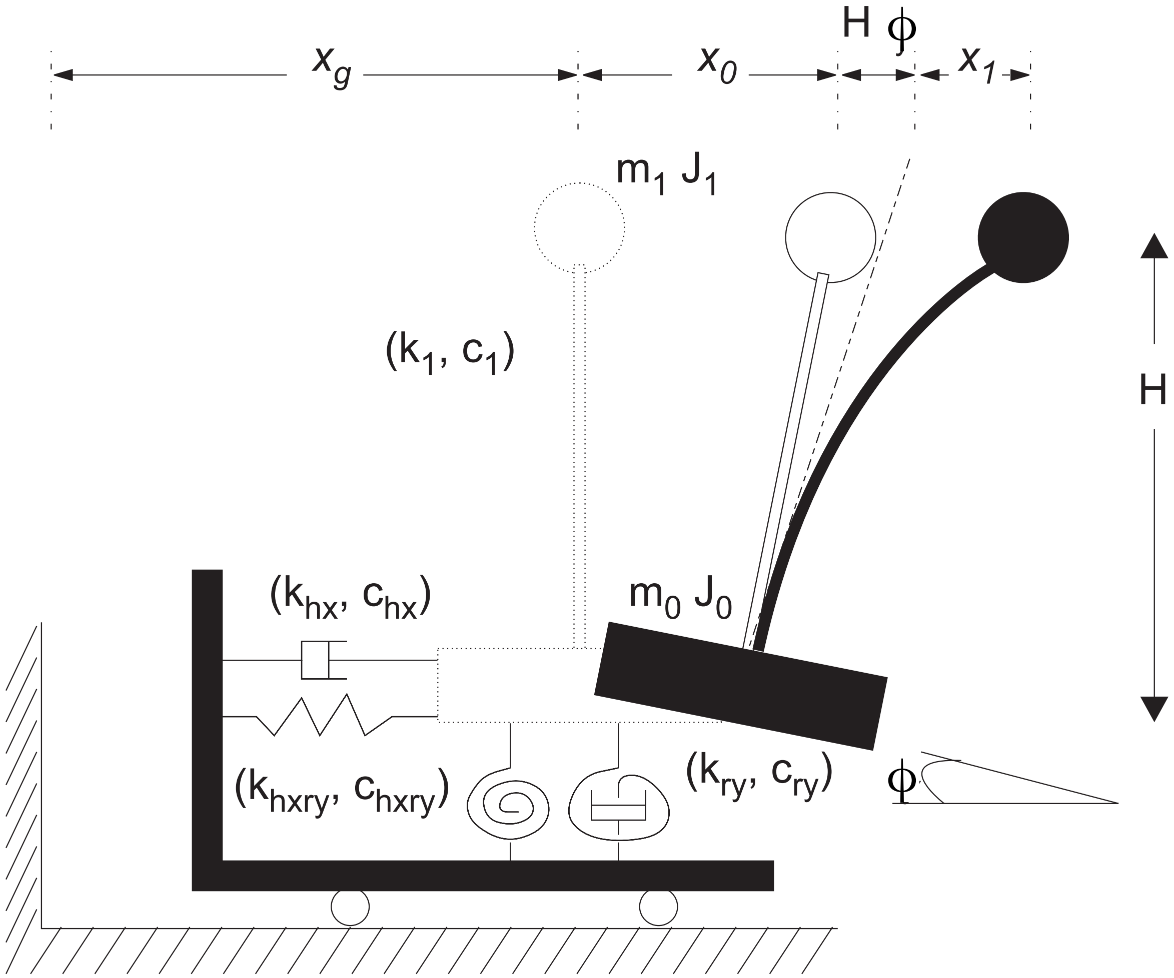


Time response of SDOF
(with f_o const., varying ζ_o)



$$\zeta = \frac{1}{2}\frac{\omega_2 - \omega_1}{\omega_r} = \frac{f_2 - f_1}{f_2 + f_1} \qquad u(t) = \frac{1}{m\omega_D}\left(\int_0^t \ddot{u}_g(\tau)e^{-\zeta\omega(t-\tau)}\sin\omega_D(t-\tau)d\tau\right)$$

Structural dynamics



$F=KU$

$K = k_{stat}\,(k_x+i\omega c_x)$

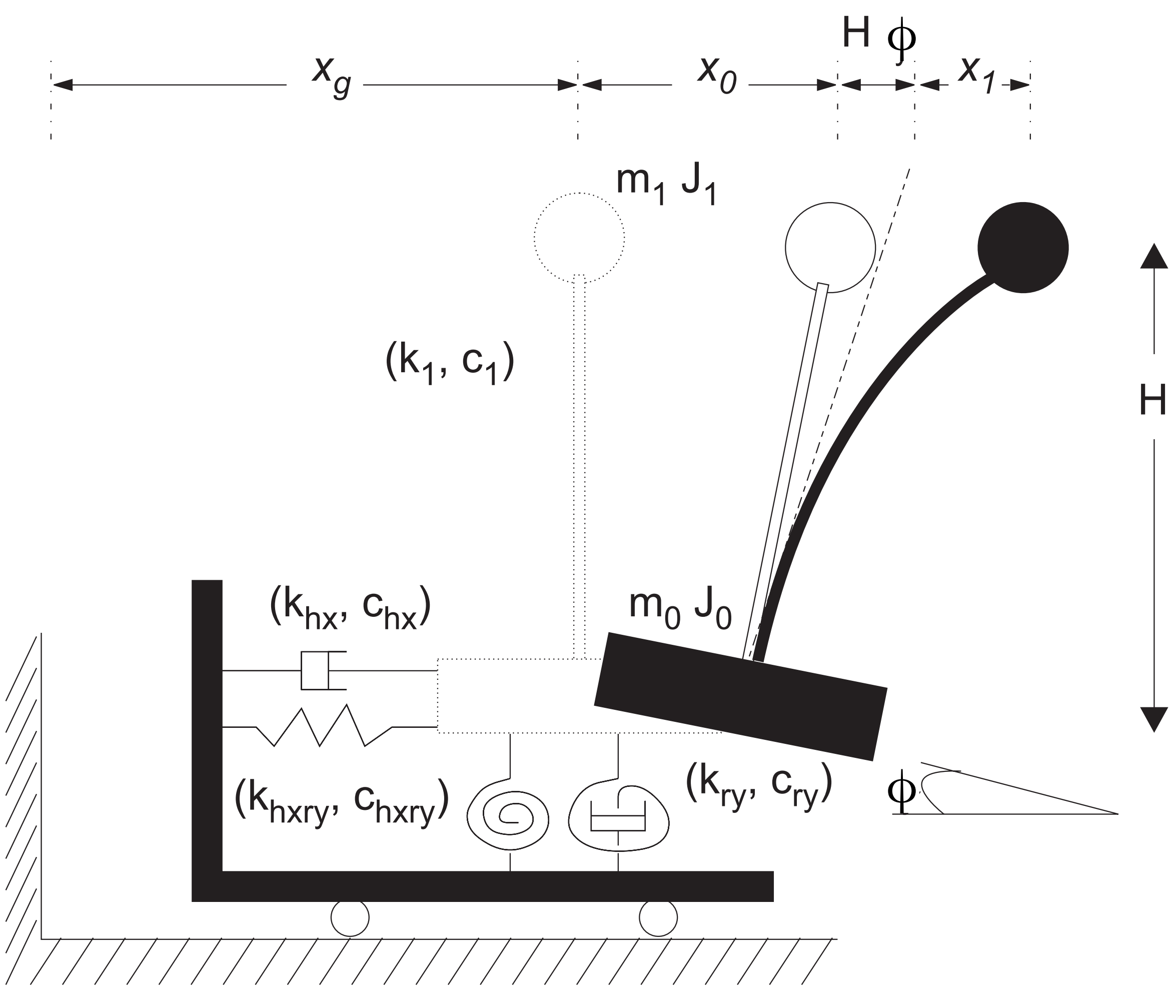
Wet sponge

Flexible-base building

Dry sponge

Fixed-base building

Structural dynamics



X_g=input seismic motion
X_0=relative motion of m_0
X_1=inertial motion of m_1
Φ=rocking motion

k_1,c_1: stifness and damping coefficients of the building (fixed-base)

k_{hx},c_{hx}: impedance coefficients for translation
k_{ry},c_{ry}: impedance coefficients for rocking
k_{hxry},c_{hxry}: impedance coefficients for translation/rocking coupling

$$\mathrm{m}_1: \quad m_1(\ddot{x}_1 + \ddot{x}_0 + H\ddot{\phi}_y) + c_1\dot{x}_1 + k_1 x_1 = -m_1\ddot{x}_g$$

$$\mathrm{m}_0: \quad m_0\ddot{x}_0 + \tilde{c}_{hx}\dot{x}_0 + \tilde{k}_{hx}x_0 + \tilde{c}_{hxry}\dot{\phi}_y + \tilde{k}_{hxry}\phi_y - c_1\dot{x}_1 - k_1 x_1 = -m_0\ddot{x}_g$$

$$J_0\ddot{\phi}_y + \tilde{c}_{ry}\dot{\phi}_y + \tilde{k}_{ry}\phi_y + \tilde{c}_{ryhx}\dot{x}_0 + \tilde{k}_{ryhx}x_0 - Hc_1\dot{x}_1 - Hk_1 x_1 = 0$$

Structural dynamics

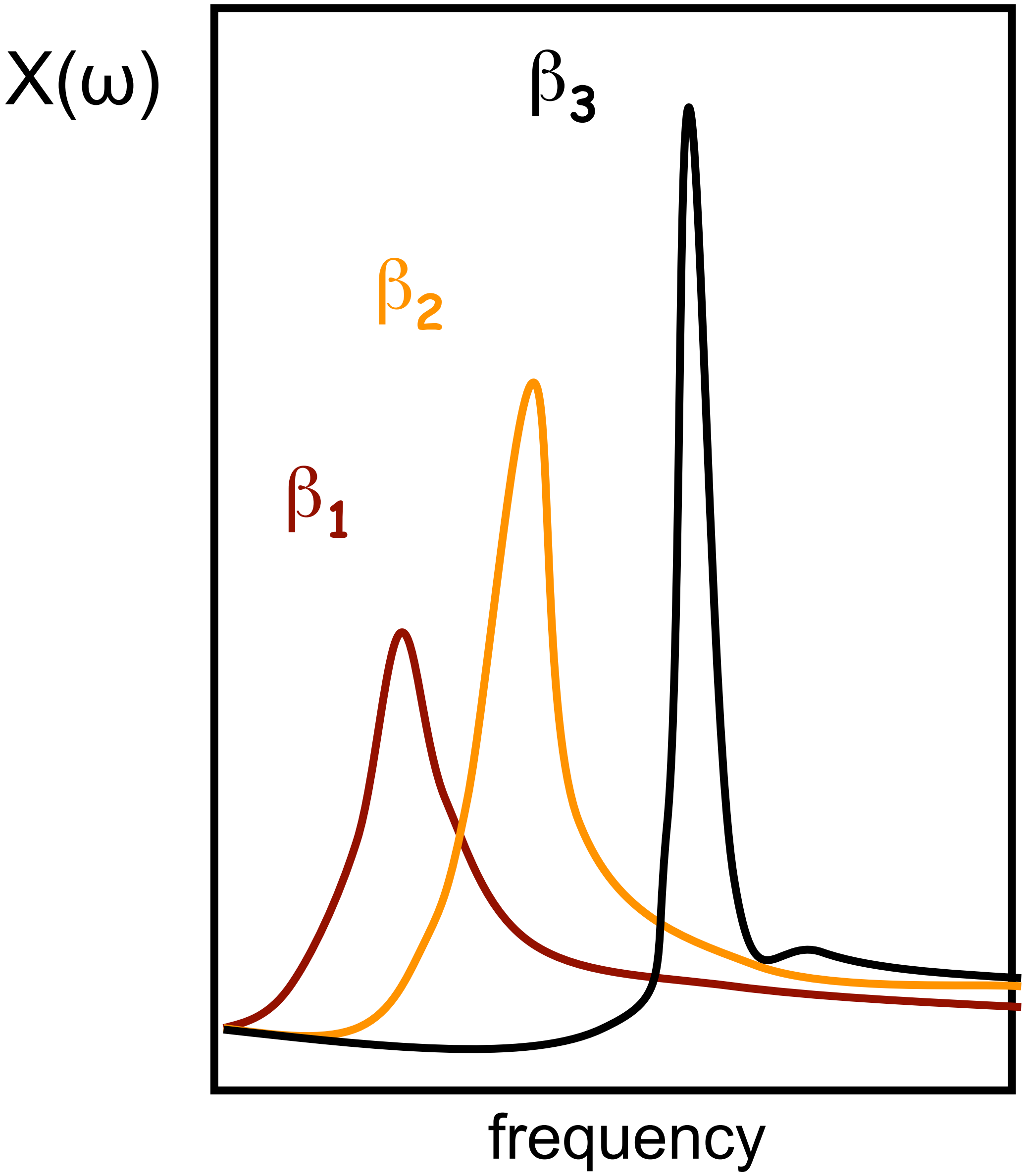
$$\{X\}(\omega) = \frac{\{-\hat{m}\}\, X_g(\omega)\omega^2}{[K_t] - [M]\,\omega^2}$$

Stewart and Fenves, 2005

$$\frac{1}{\widetilde{\omega}^2} = \frac{1}{\omega_0^2} + \frac{1}{\omega_1^2} + \frac{1}{\omega_\theta^2}$$

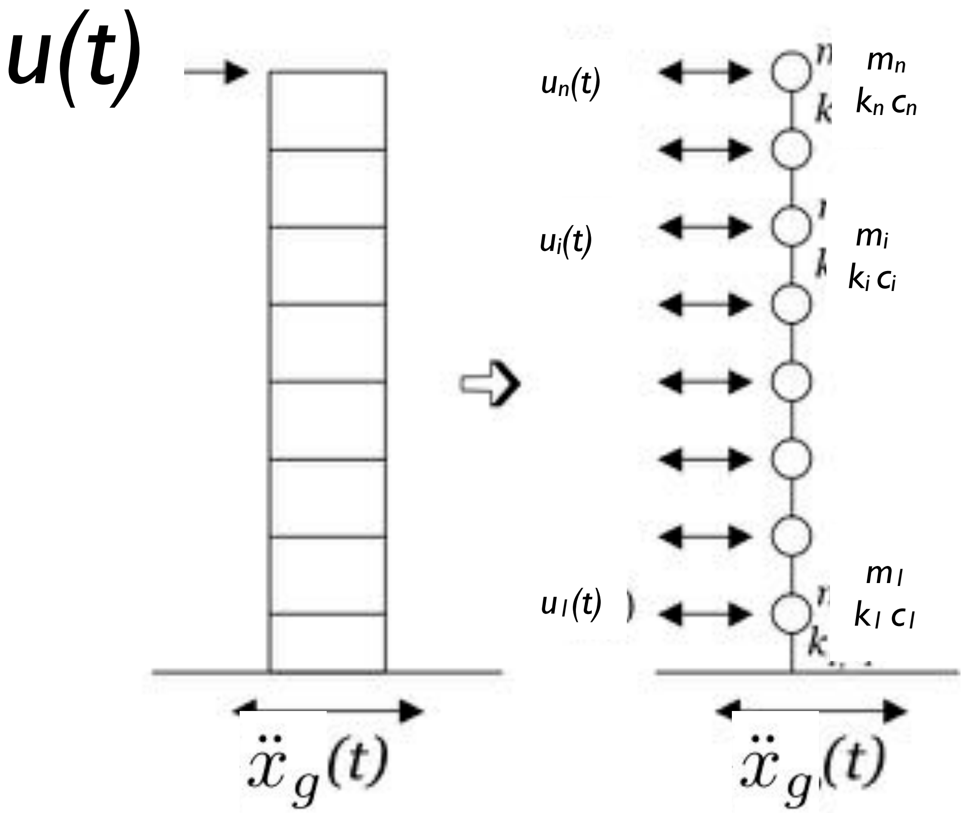
$$\frac{1}{\widetilde{\zeta}} = \left(\frac{\omega_0}{\widetilde{\omega}}\right)^3 \frac{1}{\zeta_0} + \left(\frac{\omega_1}{\widetilde{\omega}}\right)^3 \frac{1}{\zeta_1} + \left(\frac{\omega_\theta}{\widetilde{\omega}}\right)^3 \frac{1}{\zeta_\theta}$$

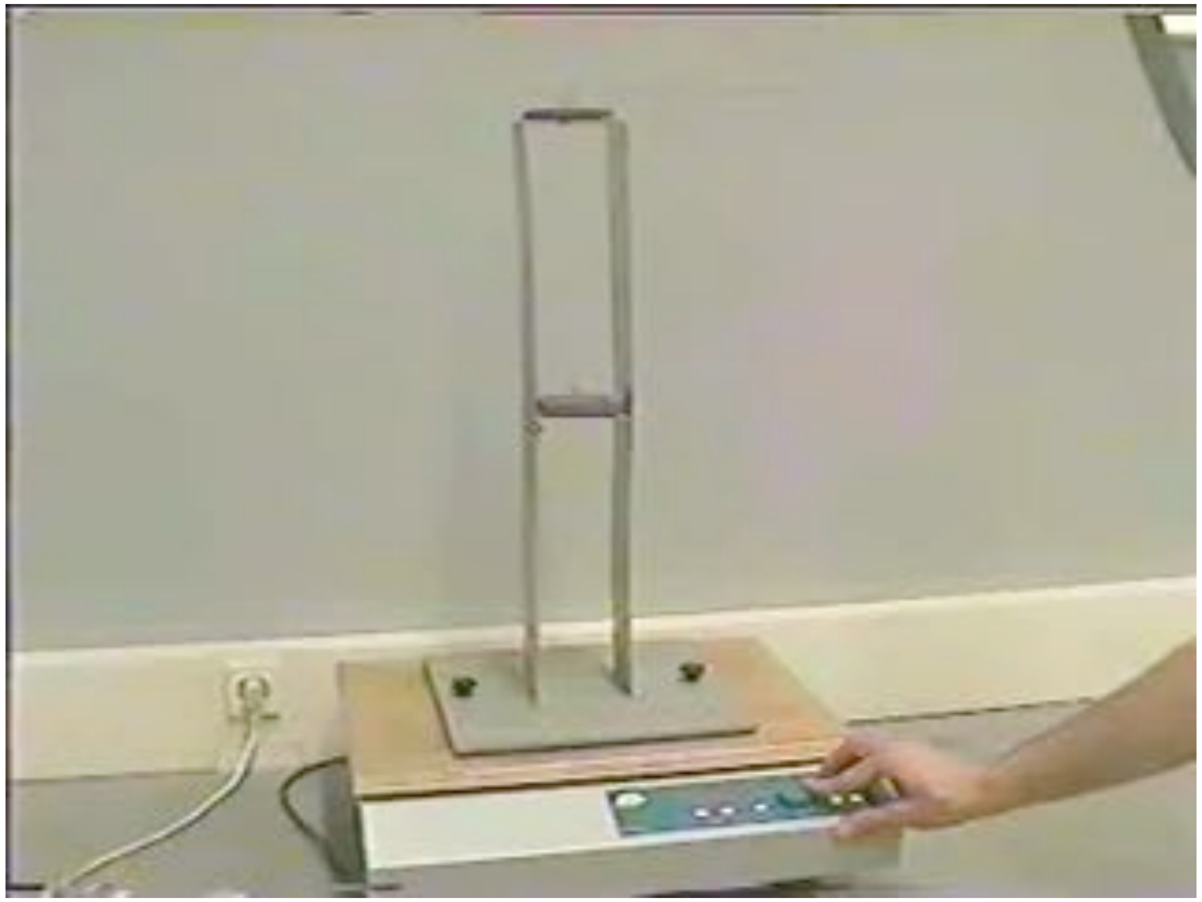
S-wave velocity $\beta_1 < \beta_2 < \beta_3$



Structural dynamics

A more realistic representation of real structures is: a multi-degree-of-freedom system MDOF





Courtesy G. Hivin UJF

Equation of motion of MDOF

$$[M]\ddot{u} + [C]\dot{u} + [K]u = -[M]\{R\}\ddot{x}_g$$

n floor system has n natural frequencies (eigenvalues) and n associated modeshapes (eigenvectors)

Structural dynamics

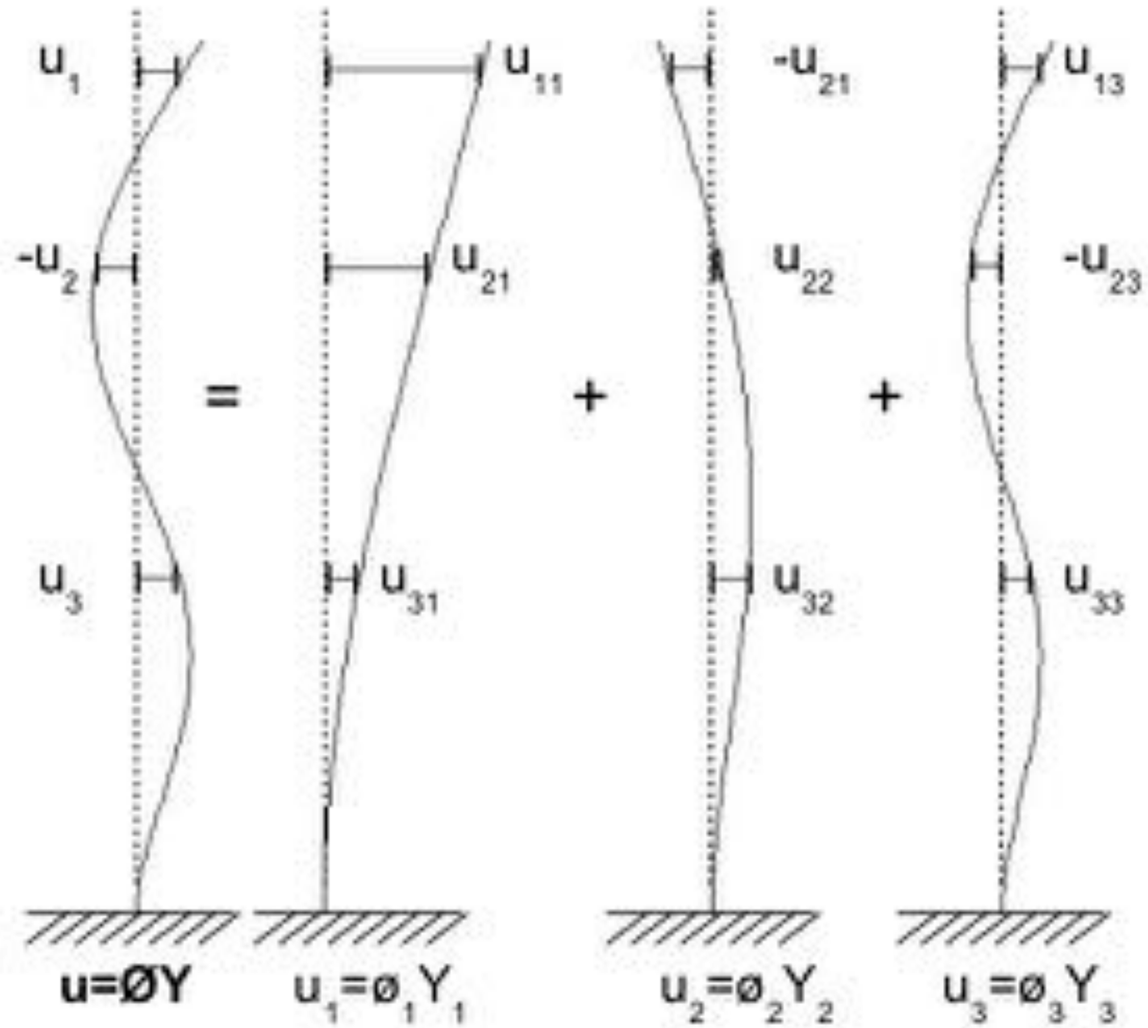
$$u_n(t) = \frac{-\phi_n^T[M]\{R\}}{M_n\omega_{Dn}}\left(\int_0^t \ddot{u}_g(\tau)e^{-\zeta_n\omega_n(t-\tau)}\sin\omega_{Dn}(t-\tau)\right)$$

Orthogonality of the modes

$$\{\phi_j\}^T[M]\{\phi_i\} = 0$$

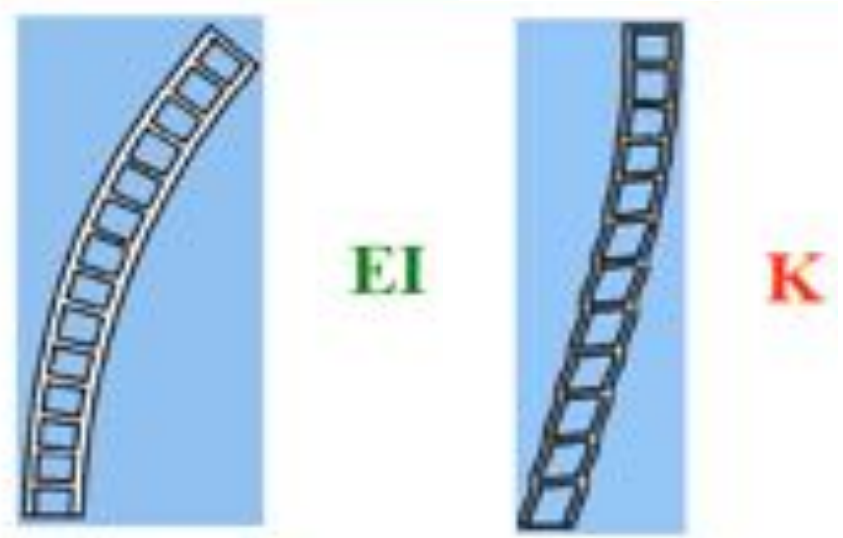
$$\{\phi_j\}^T[K]\{\phi_i\} = 0$$

$$\mathbf{u} = \phi_1 Y_1 + \phi_2 Y_2 + ... + \phi_n Y_n = \sum_{i=1}^{n}\phi_i Y_i$$



Structural dynamics

Constant mass and stiffness



Euler-Bernoulli beam (Cantilever or bending beam)

$$\frac{\partial^4 u(x,t)}{\partial x^4} + \frac{m}{EI}\frac{\partial^2 u(x,t)}{\partial t^2} = 0$$

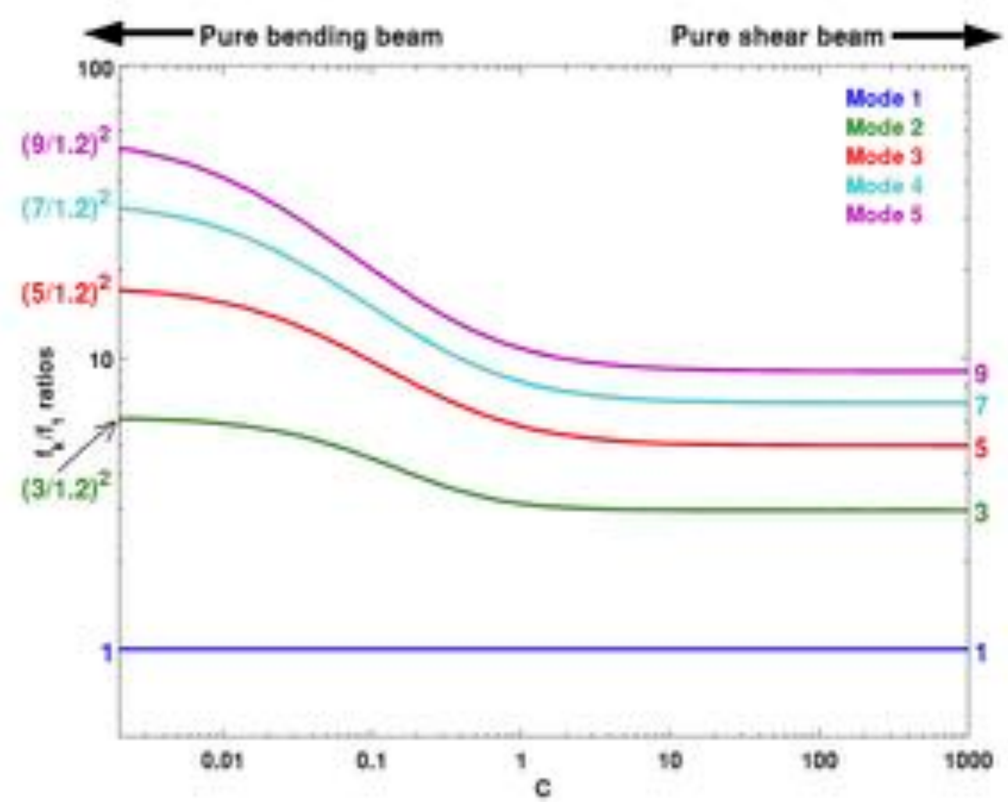
Shear beam

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{m}{KS}\frac{\partial^2 u(x,t)}{\partial t^2}$$

Timoshenko beam

$$EI\frac{\partial^4 u(x,t)}{\partial x^4} + m\frac{\partial^2 u(x,t)}{\partial t^2} - m\frac{EI}{KS}\frac{\partial^4 u(x,t)}{\partial x^2 \partial t^2} = 0$$

$$C = \frac{EI\pi^2}{4KSH^2}$$



Boutin et al., Earthq. Engng. Struct. Dyn, 2005

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Presentation Outline

Part 1: Motivation

Part 2: Structural Dynamics

Part 3: How to we get the dynamic properties ?

Part 4: Passive imaging of buildings

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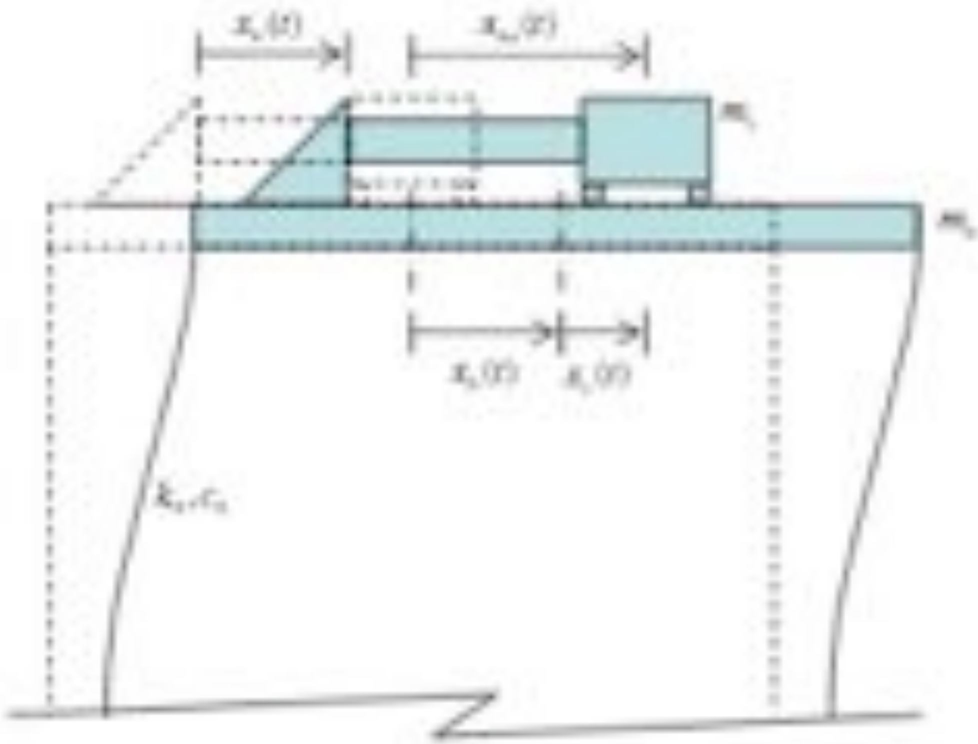
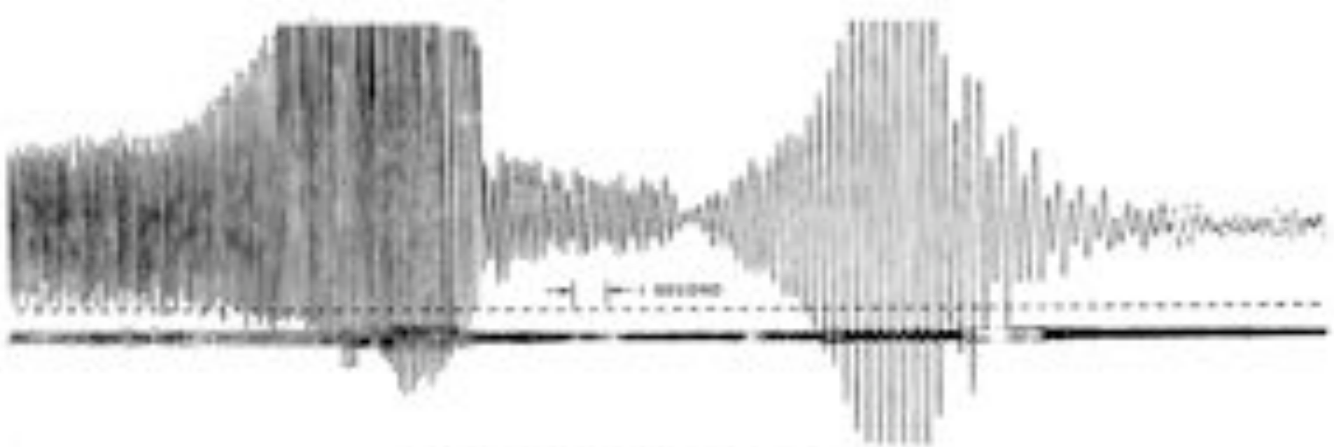
How to we get the dynamic properties ?



Asynchronous shaker at the top of the building.



J. L. ALFORD and G. W. HOUSNER
A dynamic test of a four-story reinforced concrete building
Bulletin of the Seismological Society of America, Jan 1953; 43: 7 - 16.

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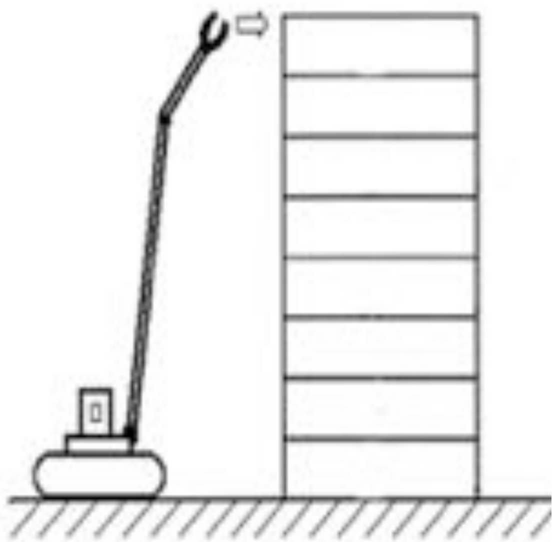
How to we get the dynamic properties ?

Bob Barret web page

How to we get the dynamic properties ?

Shocks



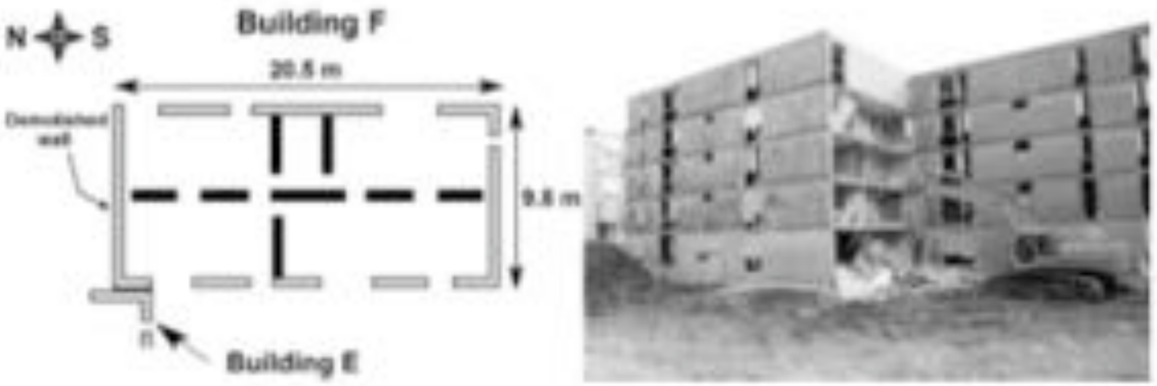
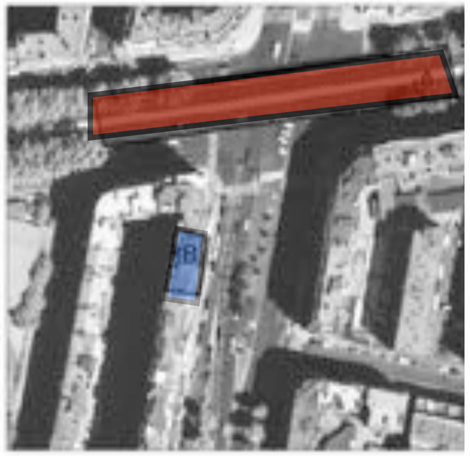
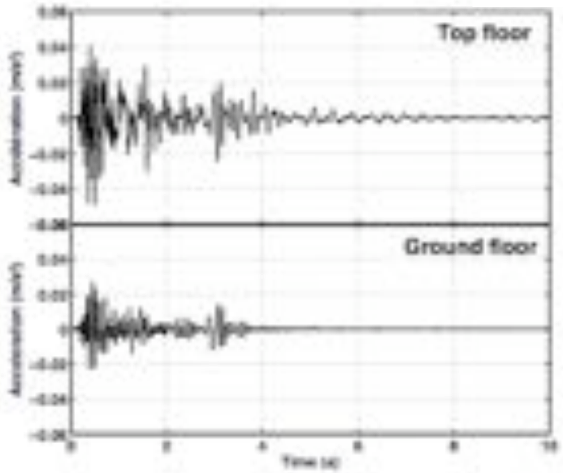


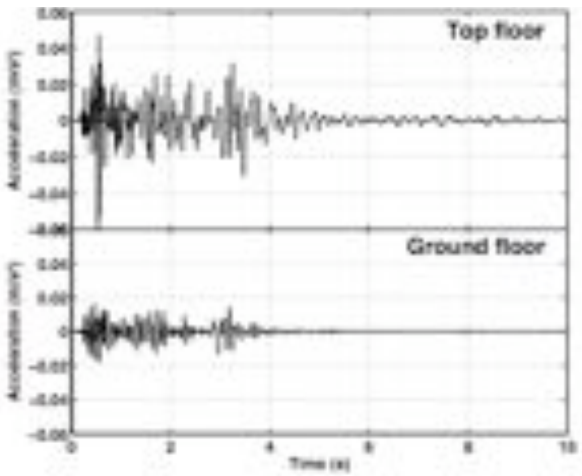
Figure 9. Modification of building F—the wall has been demolished from the base to the top of the building.

Boutin et al., EESD, 2005

Air blast or explosion







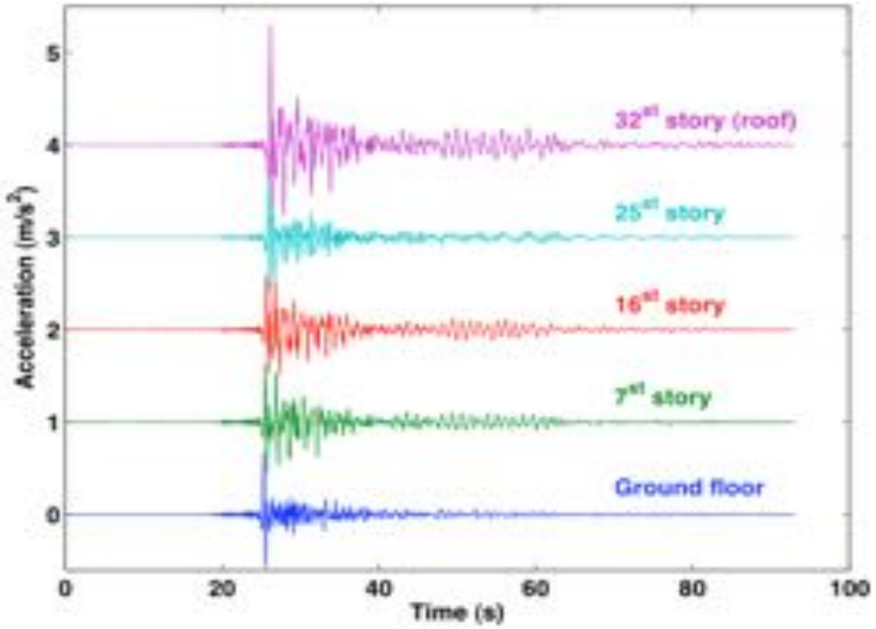
Michel et al., SDEE, 2008

How to we get the dynamic properties ?

1906: San Francisco earthquake, California.
1923: Great Kanto earthquake, Japan.

US Intrumentation Programs:
Californian Strong Motion Instrumentation Program (1960)
National Strong Motion Program (USGS)
California Strong Motion Instrumentation Program (CGS)
Buildings ~ 225 (1-62 stories high);
Code Buildings: instrumented by owner

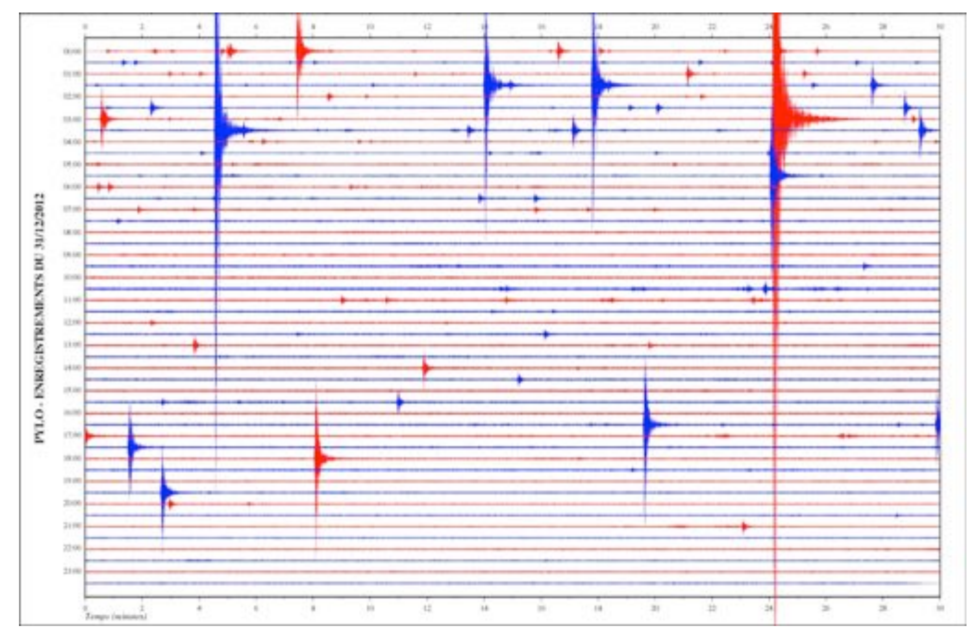
Hollywood Storage Building:
Longest history of recording in U.S. – 80 years. First record in 1933 (So. California earthquake).
Factor Building:
70 sensors in one building - On-line available data - Continuous recordings
Milikan Library:
damaged building after the San Fernando earthquake (1971) + permanent shaker at the top



How to we get the dynamic properties ?

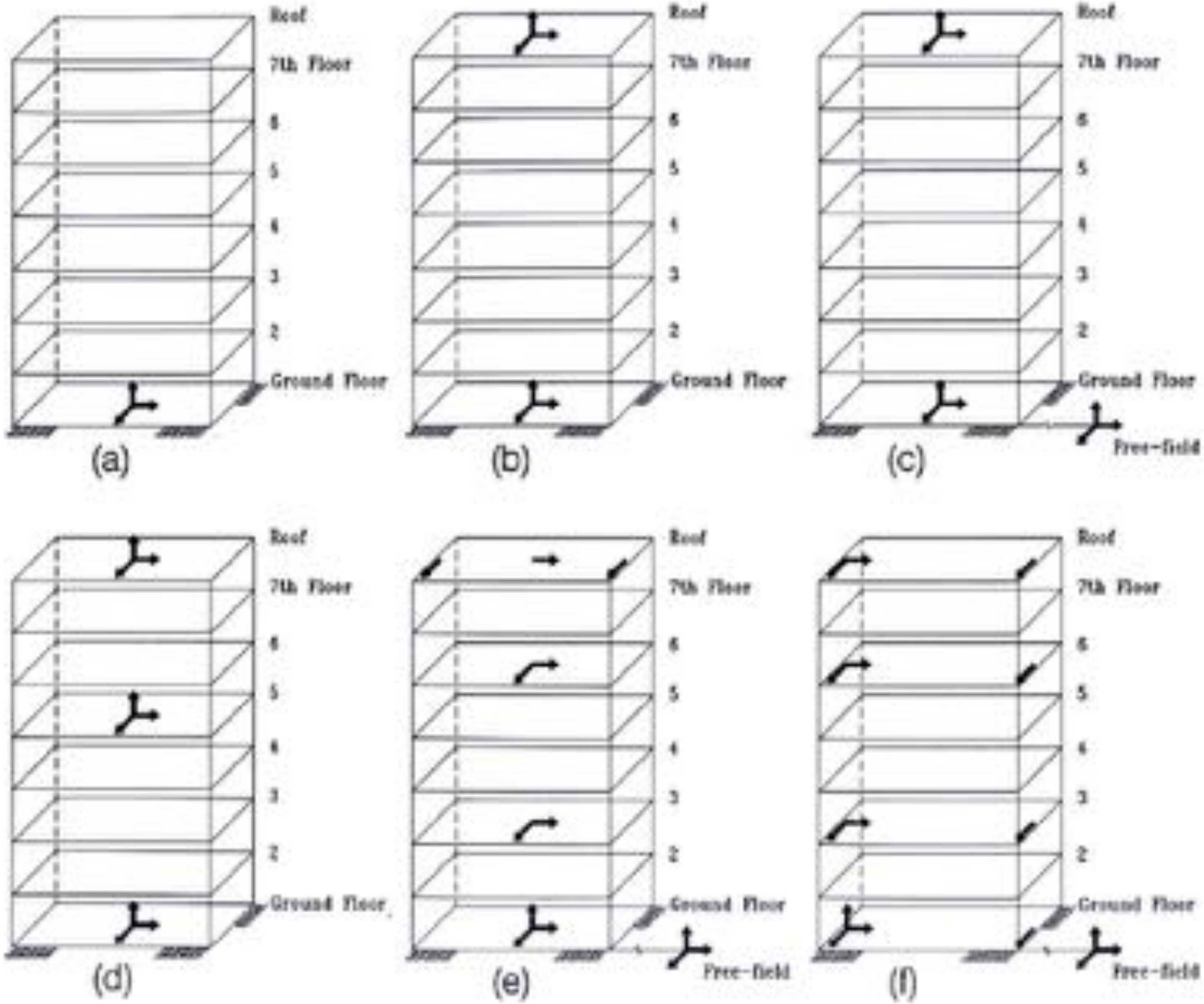
Japaneese Intrumentation Programs:
Building Research Institute BRI
Building array from 40’
1964 Nigata Earthquake - 2012 Tohoku Earthquake
74 buildings (top/bottom + boreholes st)

French Intrumentation Program:
French Acceletometric Networks (1995)
National Building Array Program (2004)
5 Buildings
- low seismicity - low sensibility
- continuous recordings
- 3 buildings in France - 2 in French west indies including one isolating rubber bearing system
- 24 channels + free-field + additional sensors



Instrumentation programs in Taiwan, Romania, Greece, Italy, Turkey ... but data are not available online

How to we get the dynamic properties ?

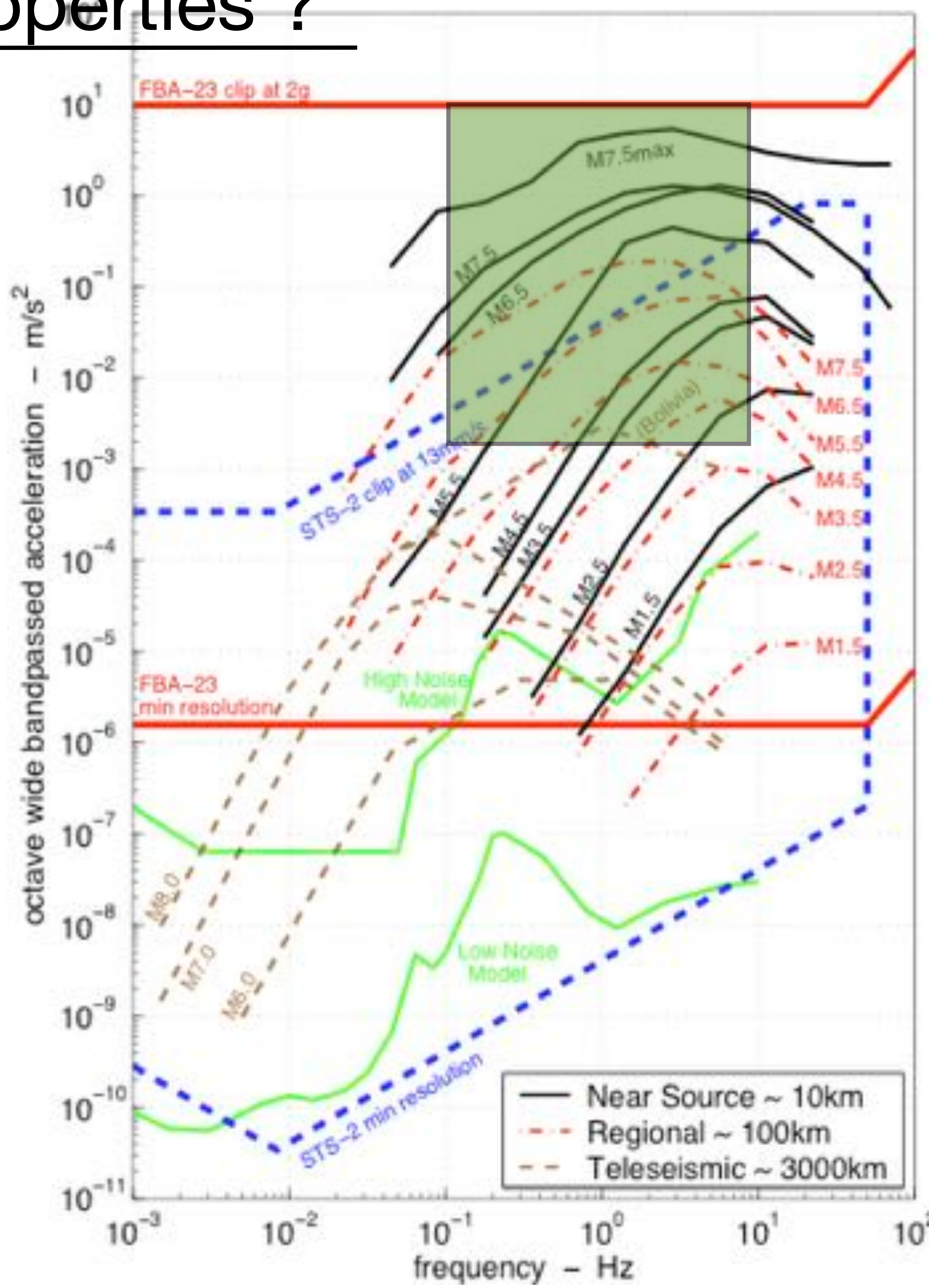


Celebi, 1998

How to we get the dynamic properties ?

Dynamic and frequency ranges of the typical sensors overlain on a bandpassed signal amplitude plot

➪ the first were analogue / 12bits digital triggered accelerometers. Recordings continuously misses moderate strong motion and ambient vibrations



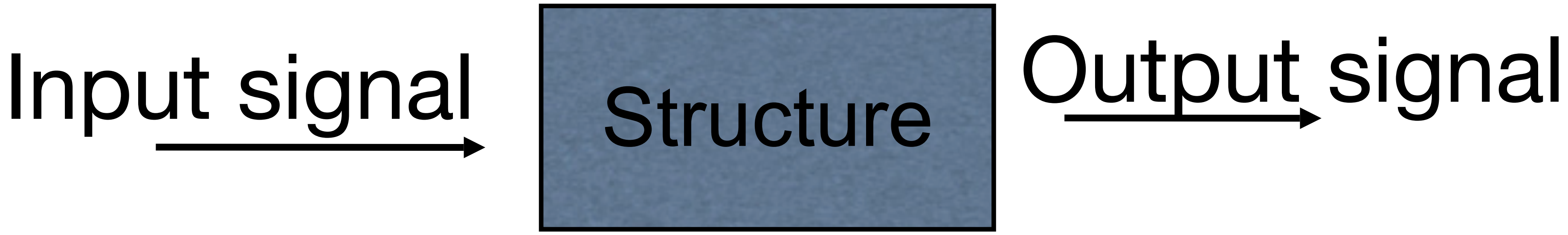
Peterson (1992) Low and High noise model

Bradford, PhD thesis 2006

How to we get the dynamic properties ?

Input/output modal analysis

- ❑Input force is measured
- ❑Output force is measured
- ❑Output is related to input through an Impulse Response Filter
- ❑IRF is independent of the input force



Time domain : Out(t)=I(t)*h(t)+n(t)

Frequency domain : H(ω)=Out(ω)/I(ω)

$$H(\omega)=\left(\frac{O(\omega)}{\max\left\{I(\omega),\,k\left(|I(\omega)|.\frac{I(\omega)}{|I(\omega)|}\right)_{\max}\right\}}\right)$$

Deconvolution (water-level)

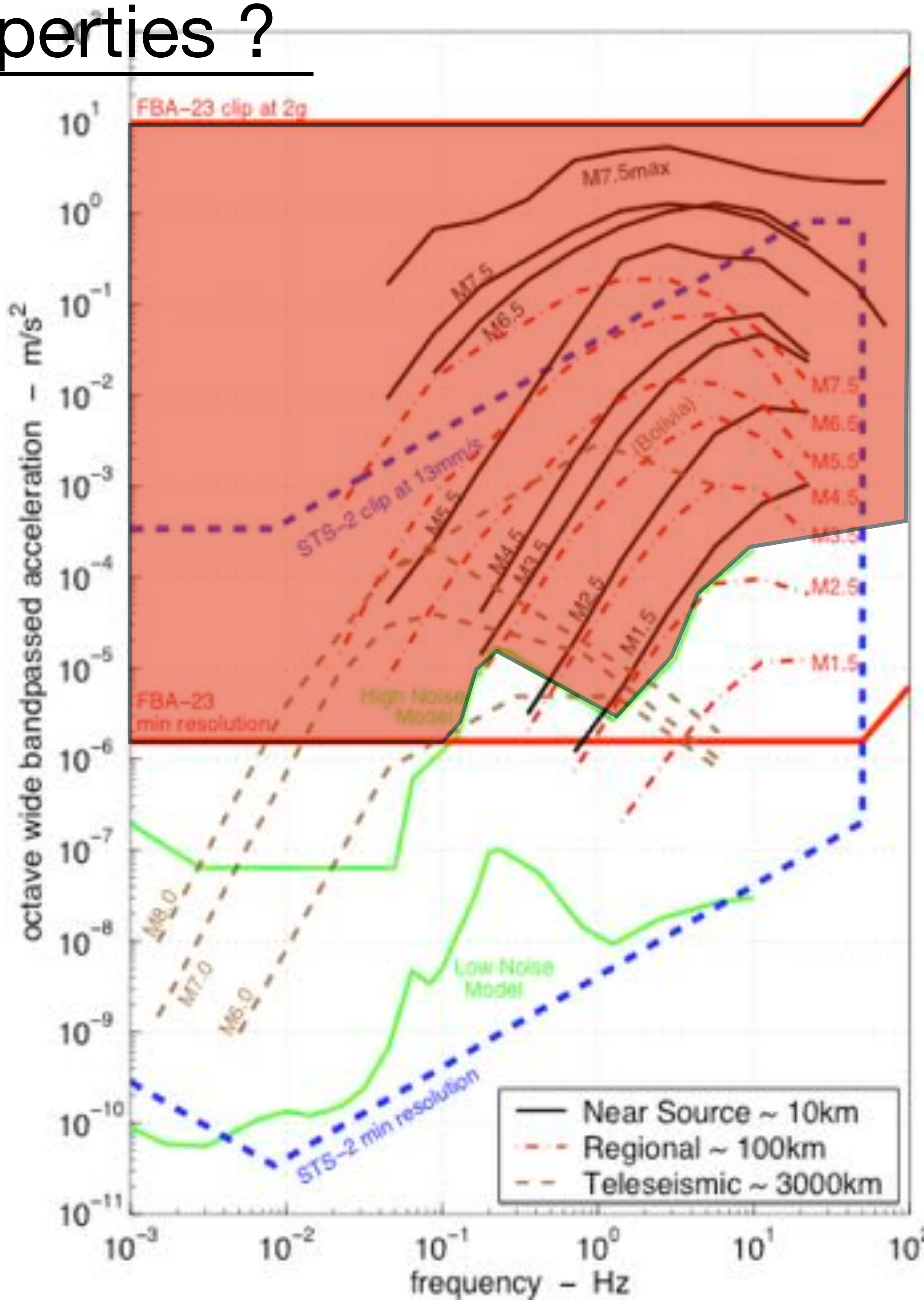
Clayton and Wiggins, J. Royal Astr. Soc. 1976

How to we get the dynamic properties ?

Dynamic and frequency ranges of the typical sensors overlain on a bandpassed signal amplitude plot

➪ the first were analogue / 12bits digital triggered accelerometer. Recording continuously misses moderate strong motion and ambient vibrations

➪ 24 bit accelerometer (begining of 90's) continuoulsy recording can record all ranges of vibration in a structure



Bradford, PhD thesis 2006

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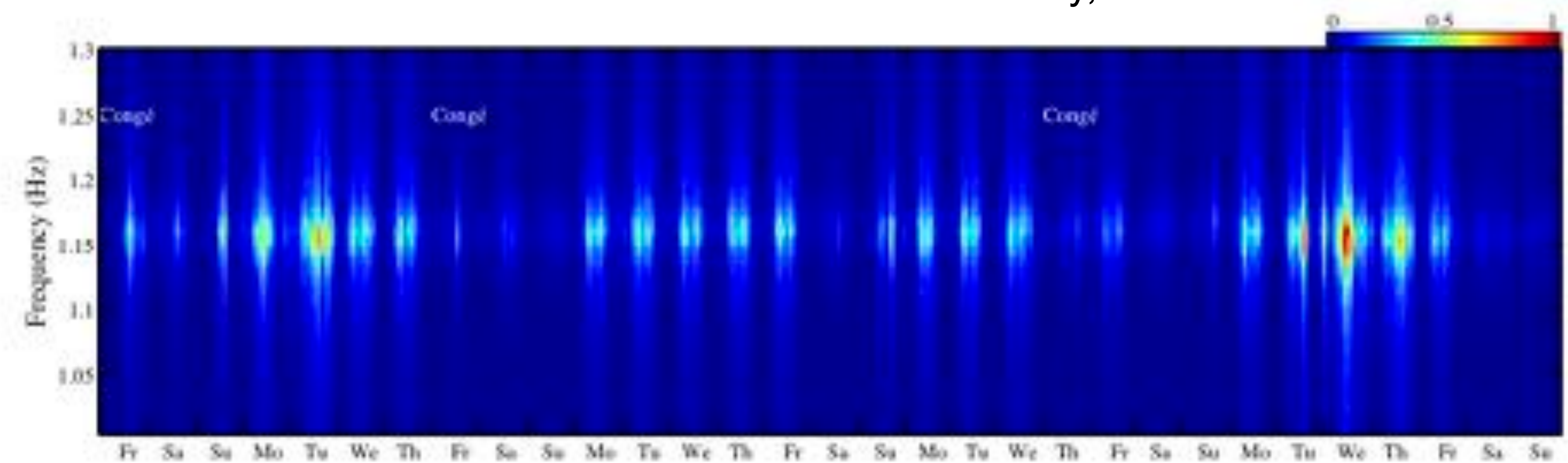
How to we get the dynamic properties ?

City-Hall Grenoble

Output-only modal analysis : Ambient vibrations

Daily variations of vibration energy

May, 2009



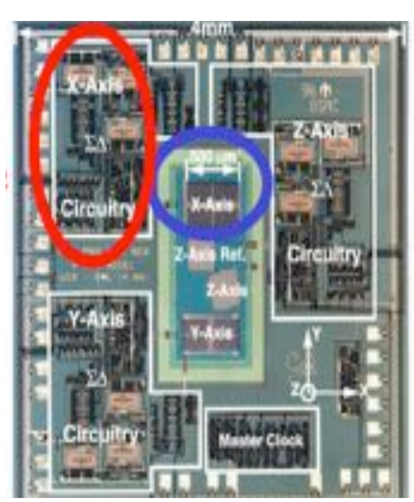
How to we get the dynamic properties ?

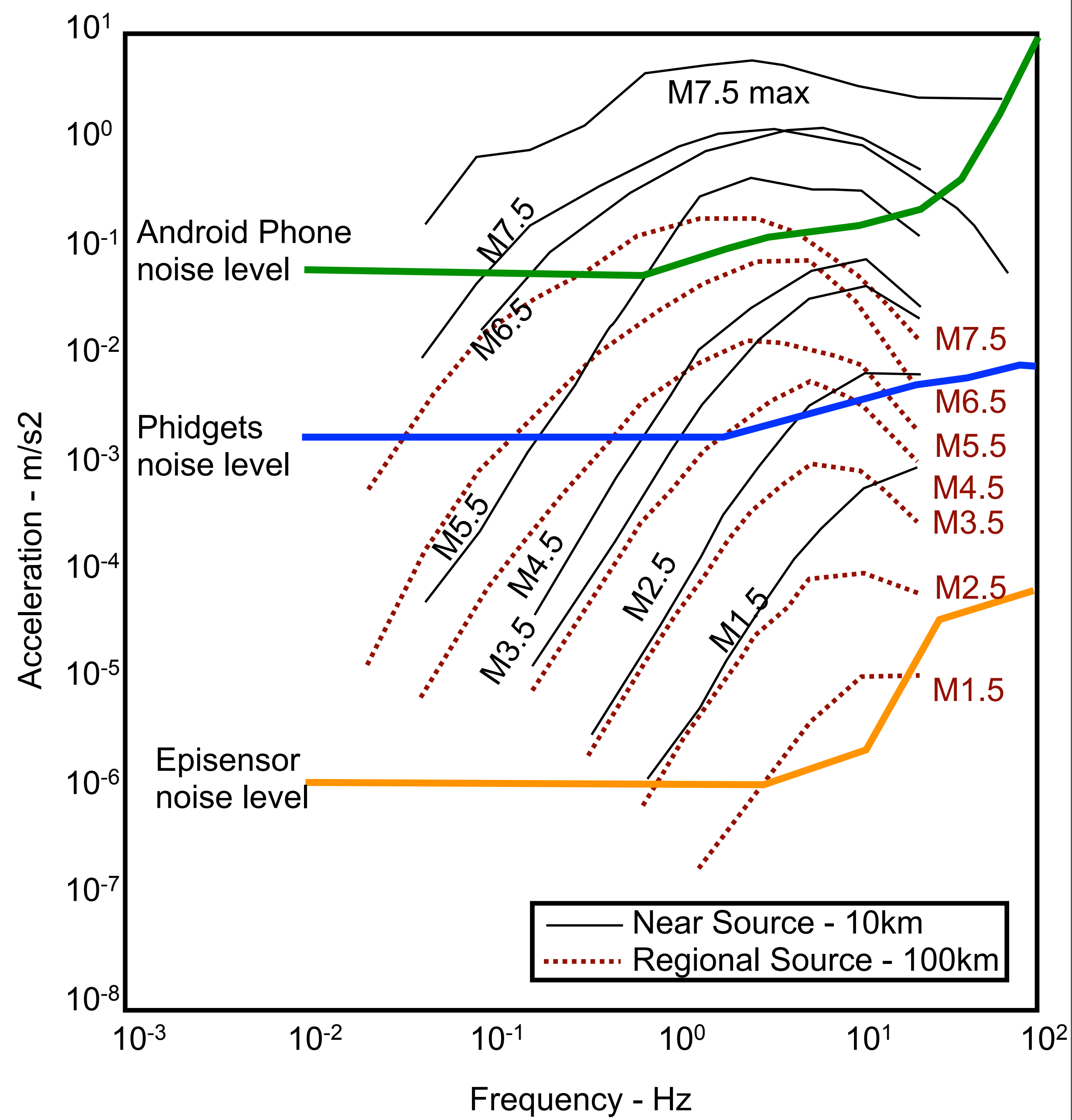
Micro-Electro-Mechanical Systems

Low cost but less sensitive.
But all types of recordings: torsion, gyroscope, GPS etc...

Characteristic of Different Instruments

	Clipping Level	Digitizer	Noise Level*	Dynamic Range	Sampling Rate
Android Phone	8g	14bits	0.0061g	62.1dB ($1.3x10^3$)	~90Hz
Phidgets	2.5g	16bits	$2.8x10^{-4}$g	78.7dB ($8.9x10^3$)	250Hz (constant)
Episensor	2g	24bits	$3.9x10^{-7}$g	133.7dB ($5.1x10^6$)	200Hz (constant)





Courtesy T. Heaton

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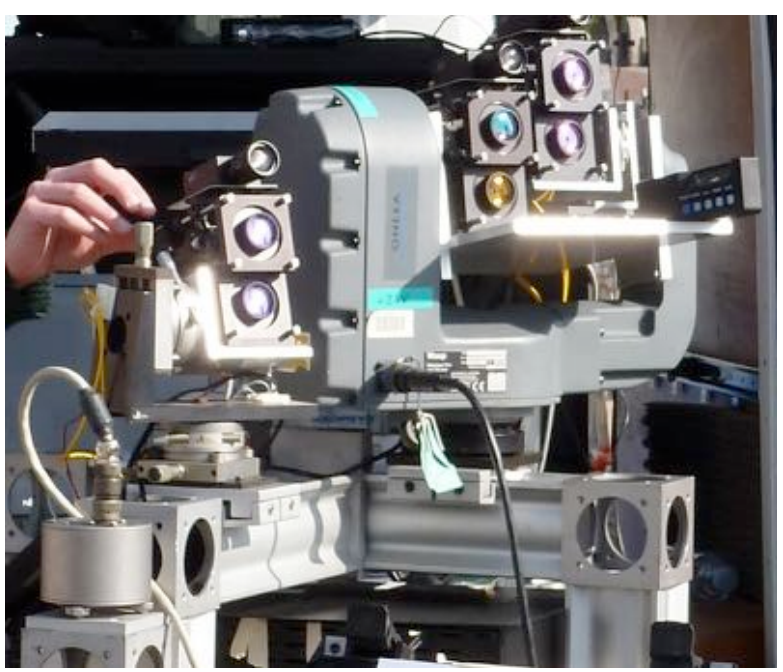
How to we get the dynamic properties ?

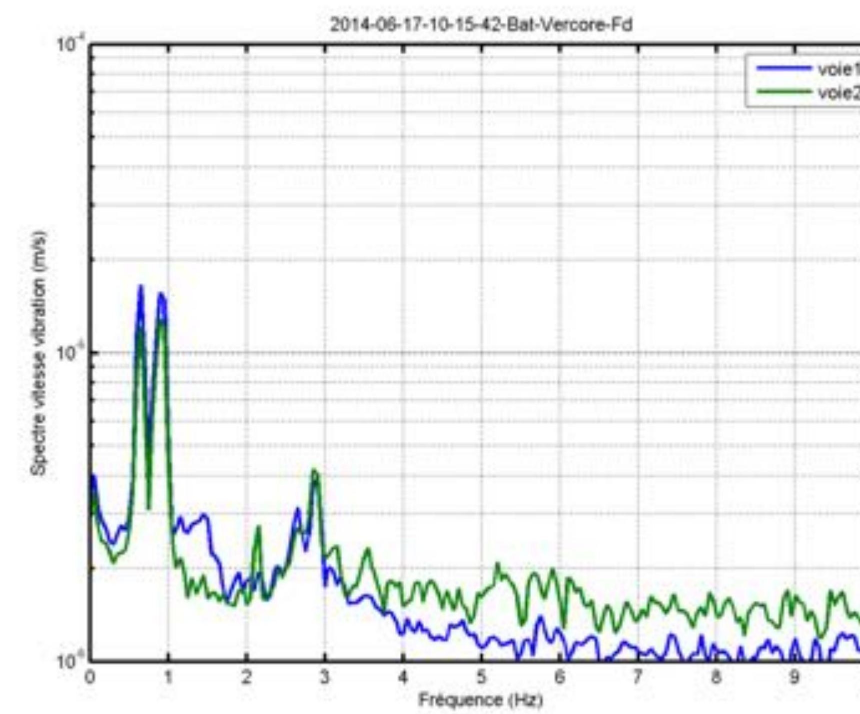
LIDAR Measurements (optical technology)

$$\nu_D = \frac{2}{\lambda} V_{building/lidar}(t).I_{lidar}$$



1.2 km

Spectres de vibration, fréquence doppler
Principales fréquences d'intérêt



Long-term monitoring of buildings from one remote reference site: successful measurements up to 5 km!

Gueguen et al., Bull. Earthq. Engng., 2010
Valla et al., ASCE Civil Engng,2014

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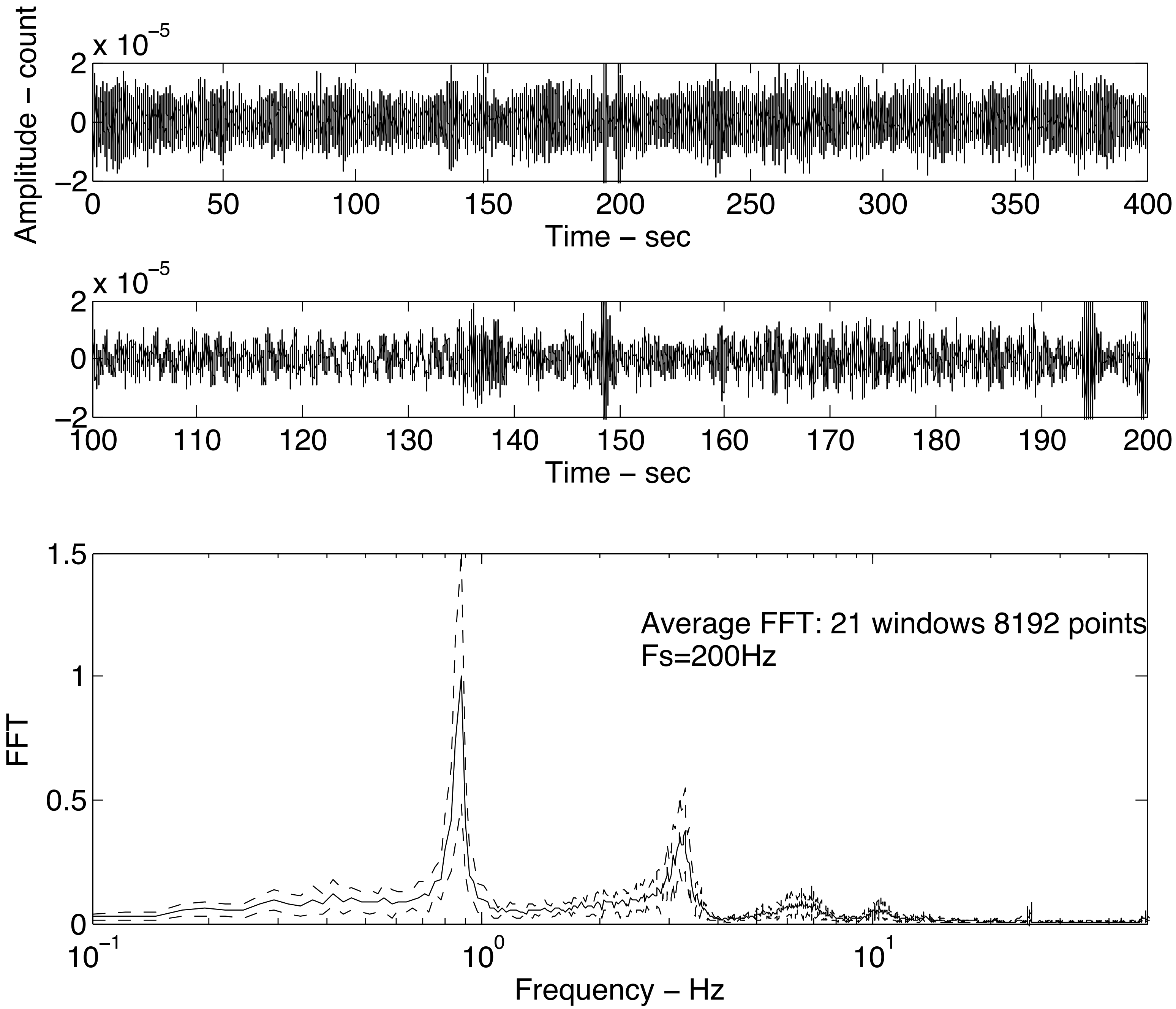
Passive imaging of buildings



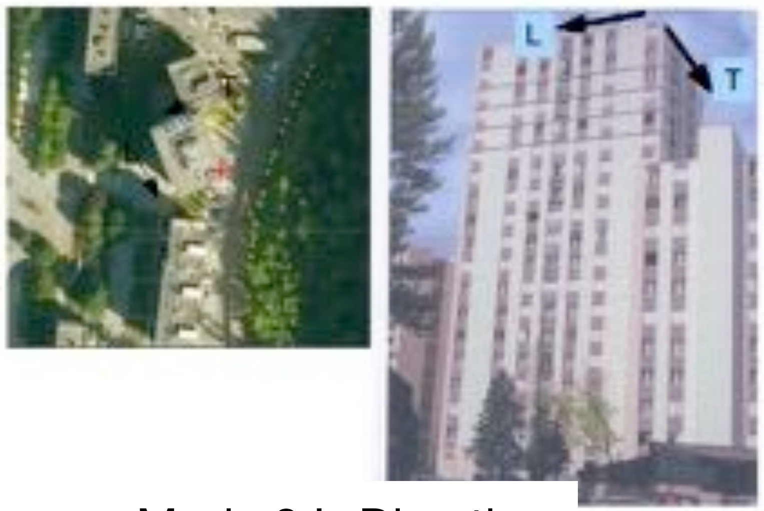
Output only - Parametric

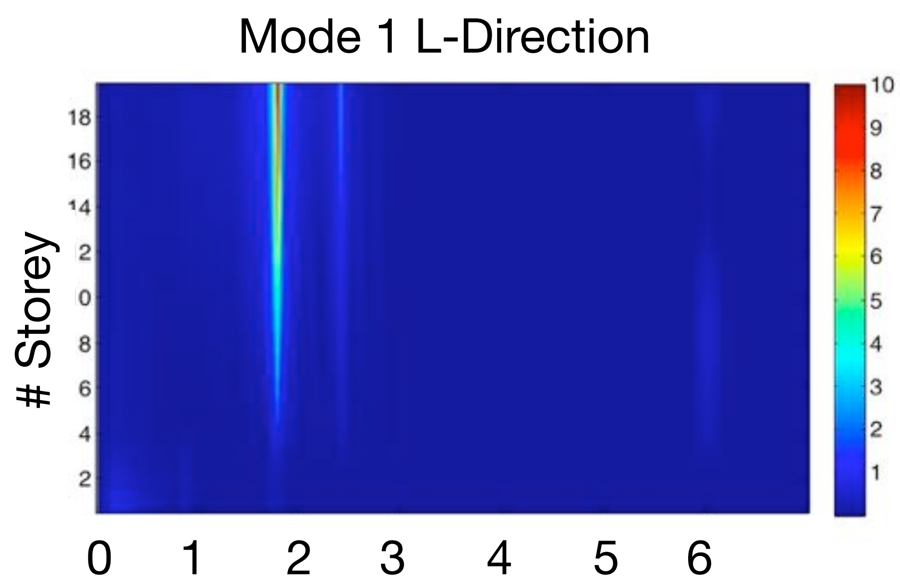
Belledonne tower
Ile Verte

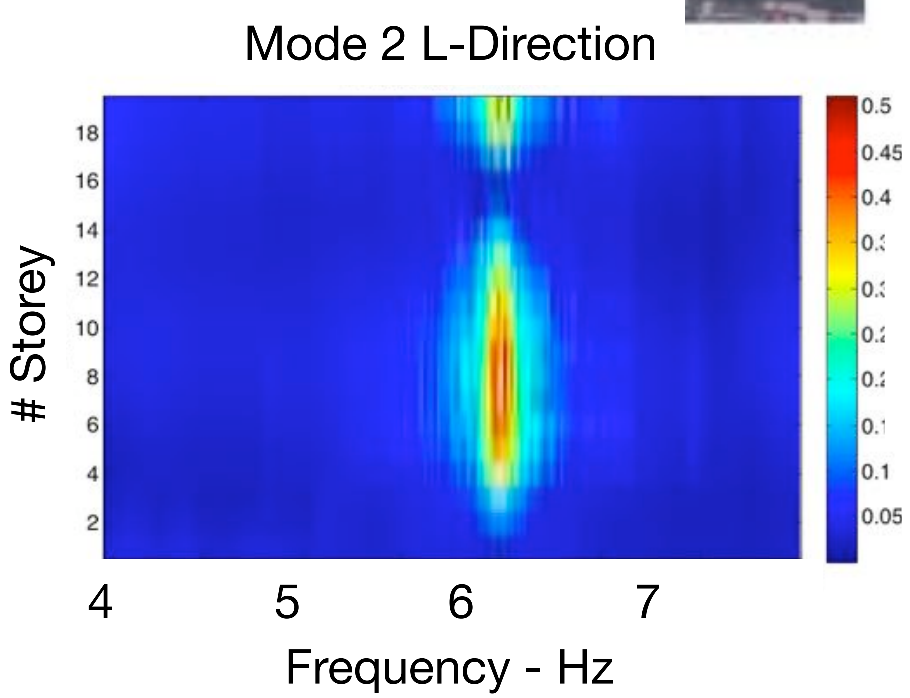
Not a new technique:

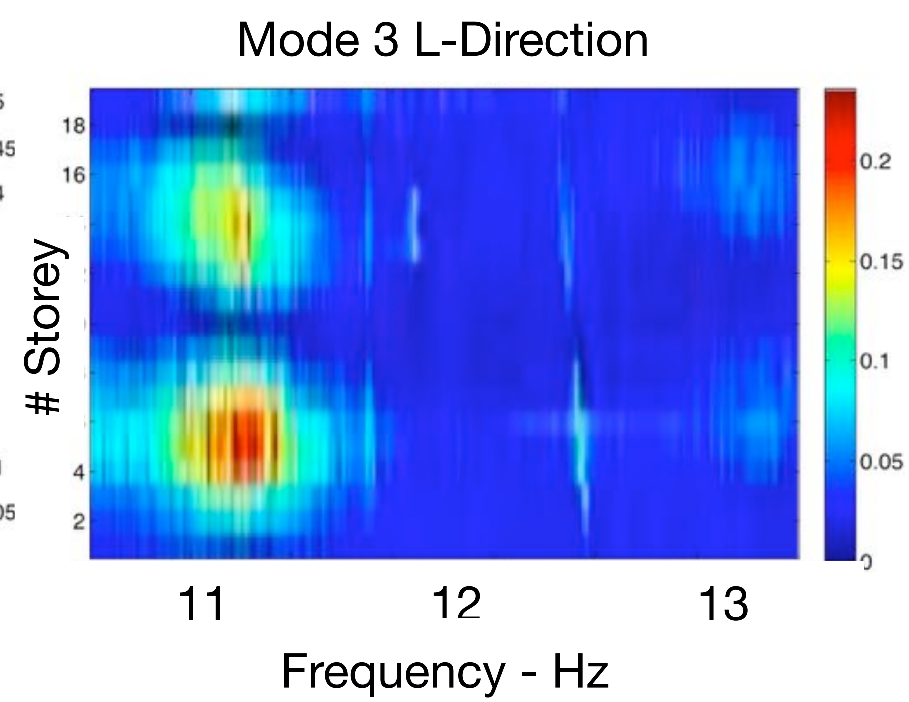
Carder D. S. Observed vibration of buildings. Bulletin of the Seismological Society of America 1936; 26:245–277.

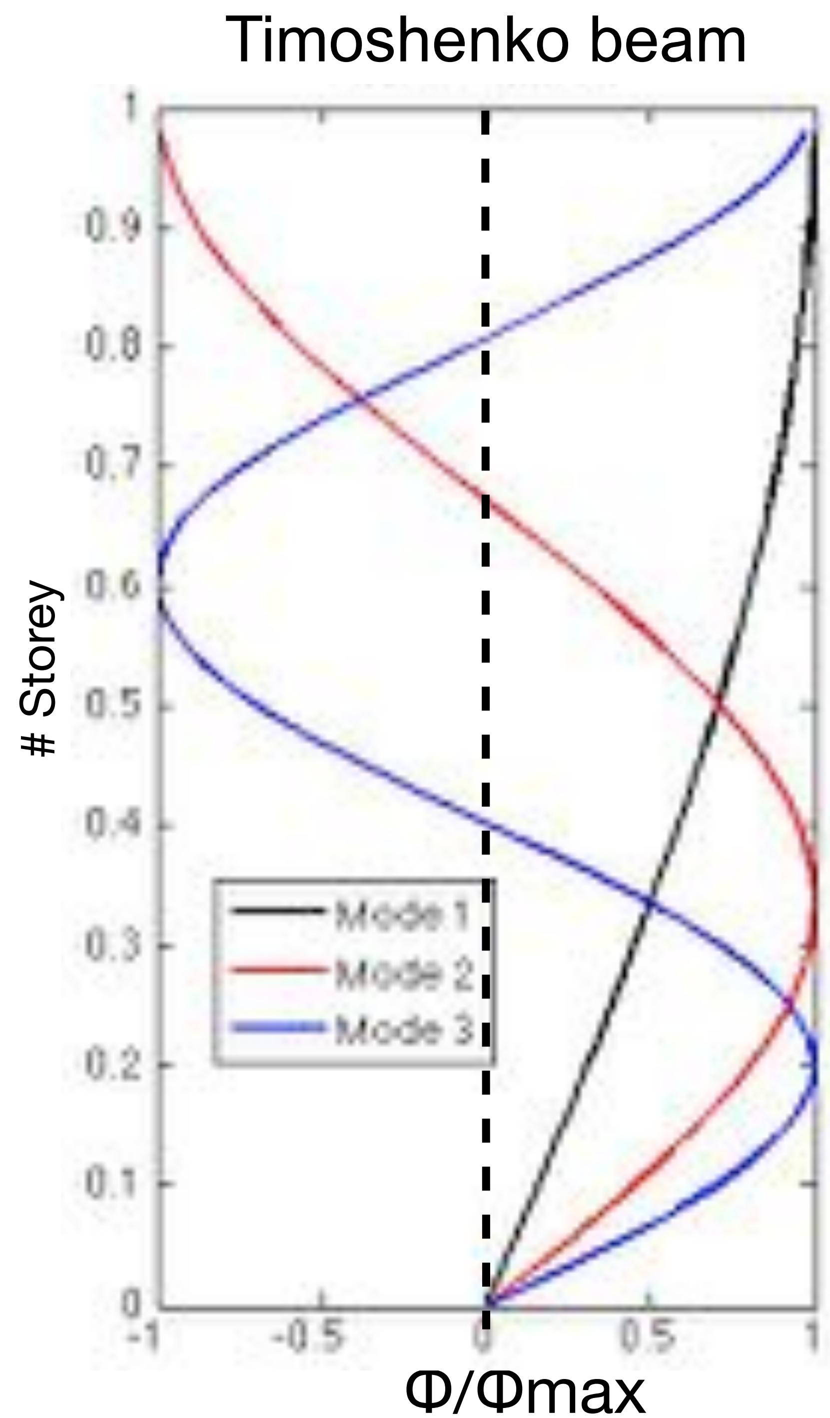
Passive imaging of buildings: Peak-picking











$f_1 = 1.9$ Hz - $f_2 = 6.1$ Hz - $f_3 = 11.4$ Hz

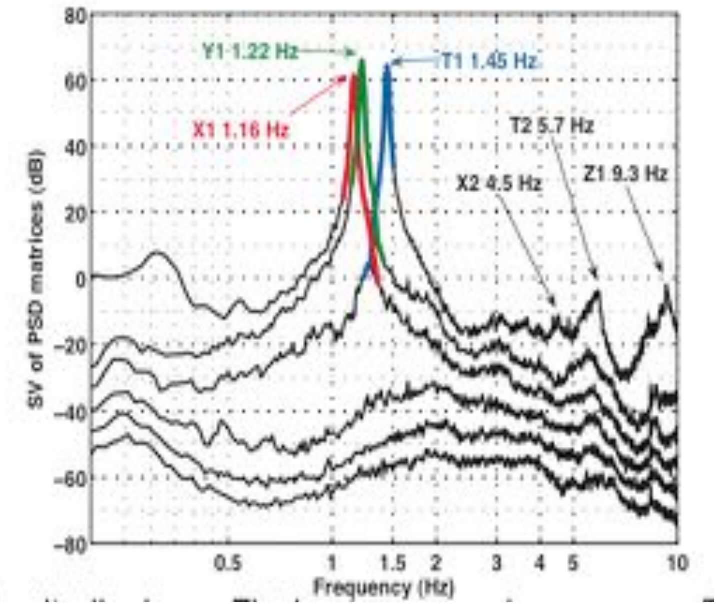
=== > $f_2 / f_1 = 3.2$ - $f_3 / f_1 = 6.0$

Passive imaging of buildings: SV decomposition

Output-only - non-parametric

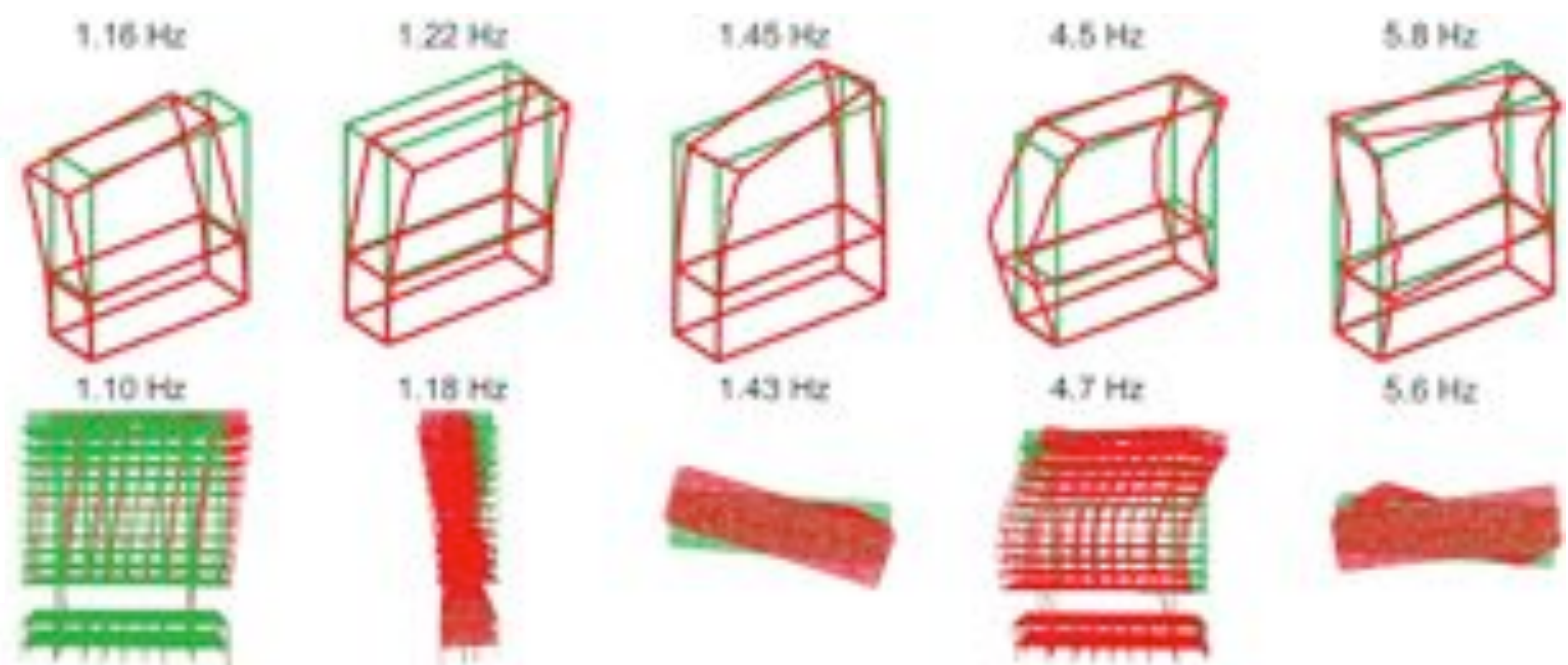
$$[S_{yy}](f) = \{Y\}^*(f)\{Y\}(f)$$

$$[S_{yy}](f_i) = [U_i][S_i][U_i]^H$$



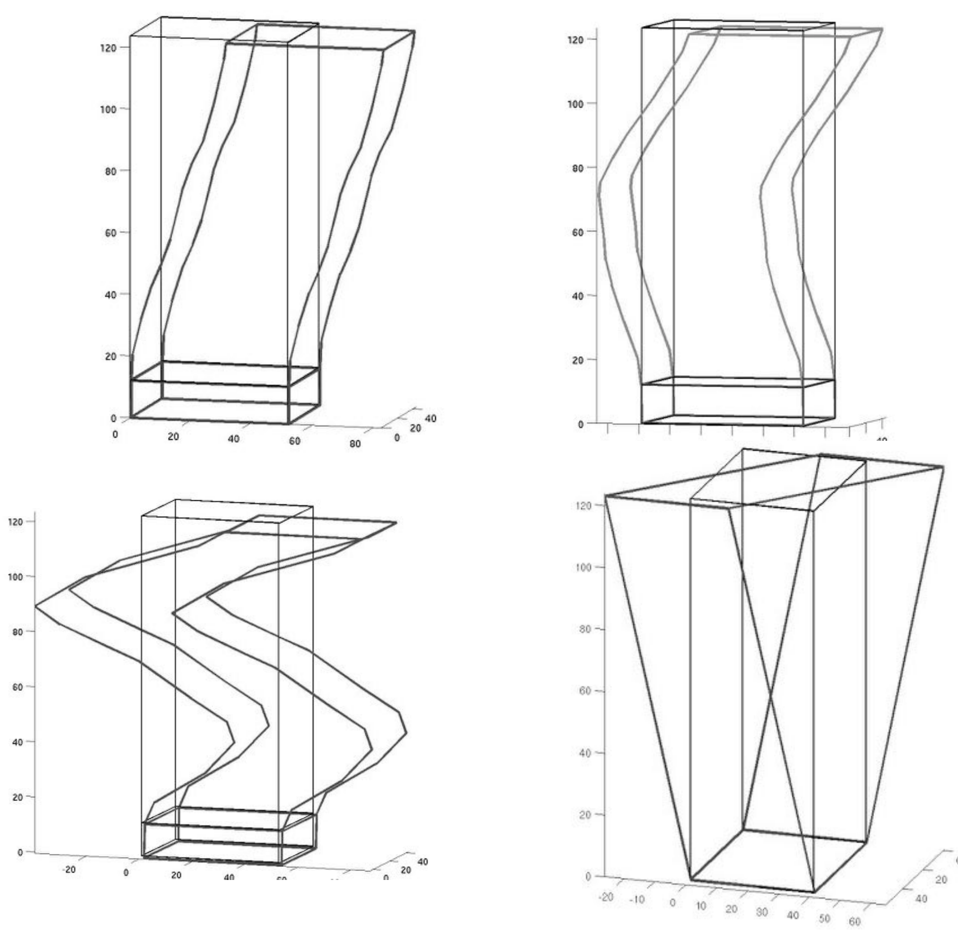
Experimental modelling

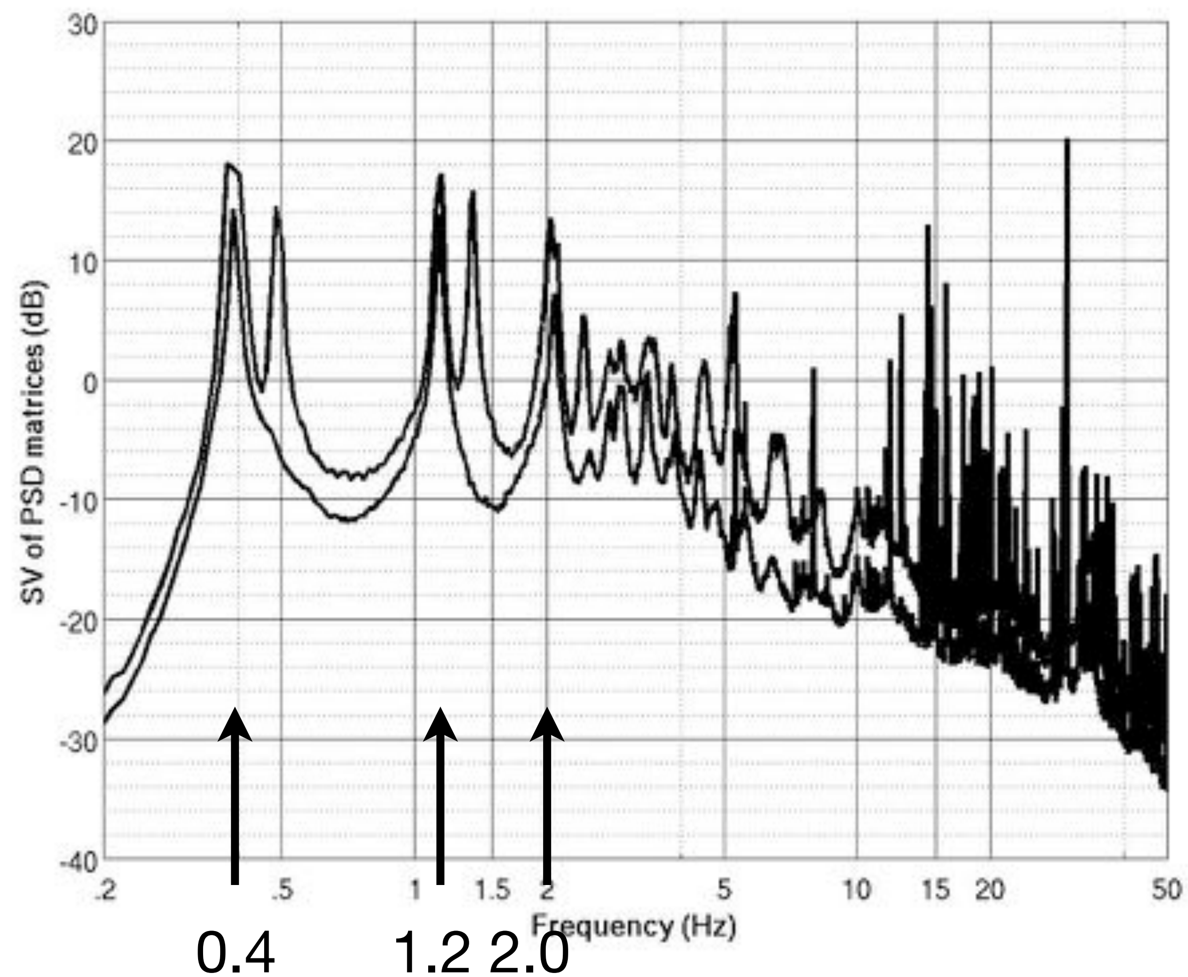
Numerical modelling



Michel et al., Earthq. Engng. Struct. Dyn., 2009

Passive imaging of buildings: SV decomposition





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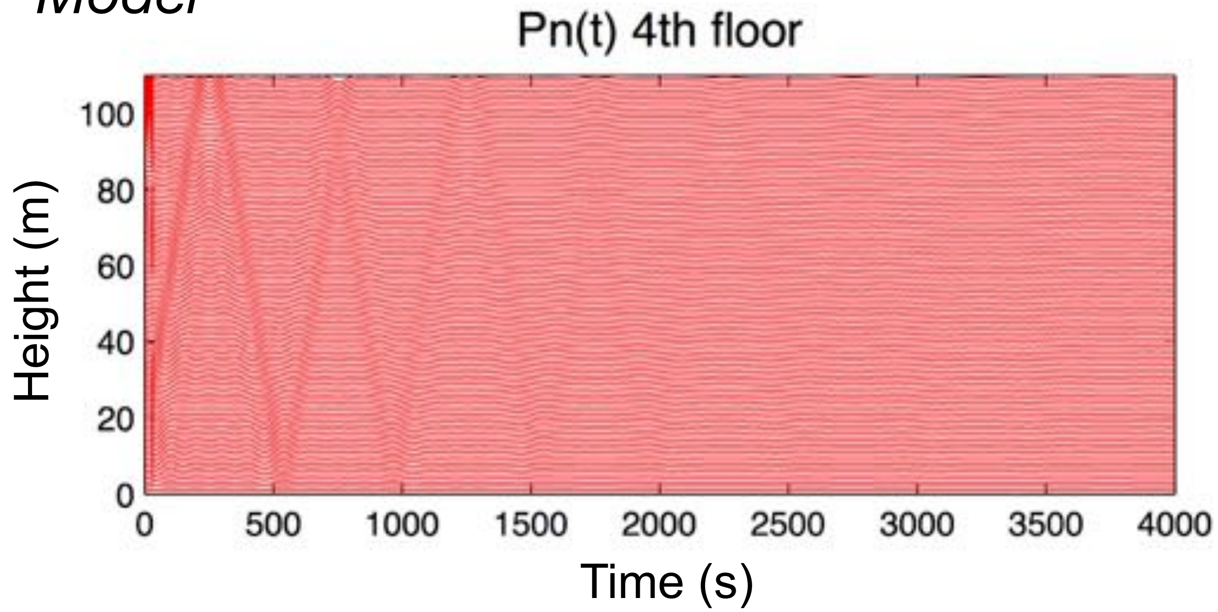
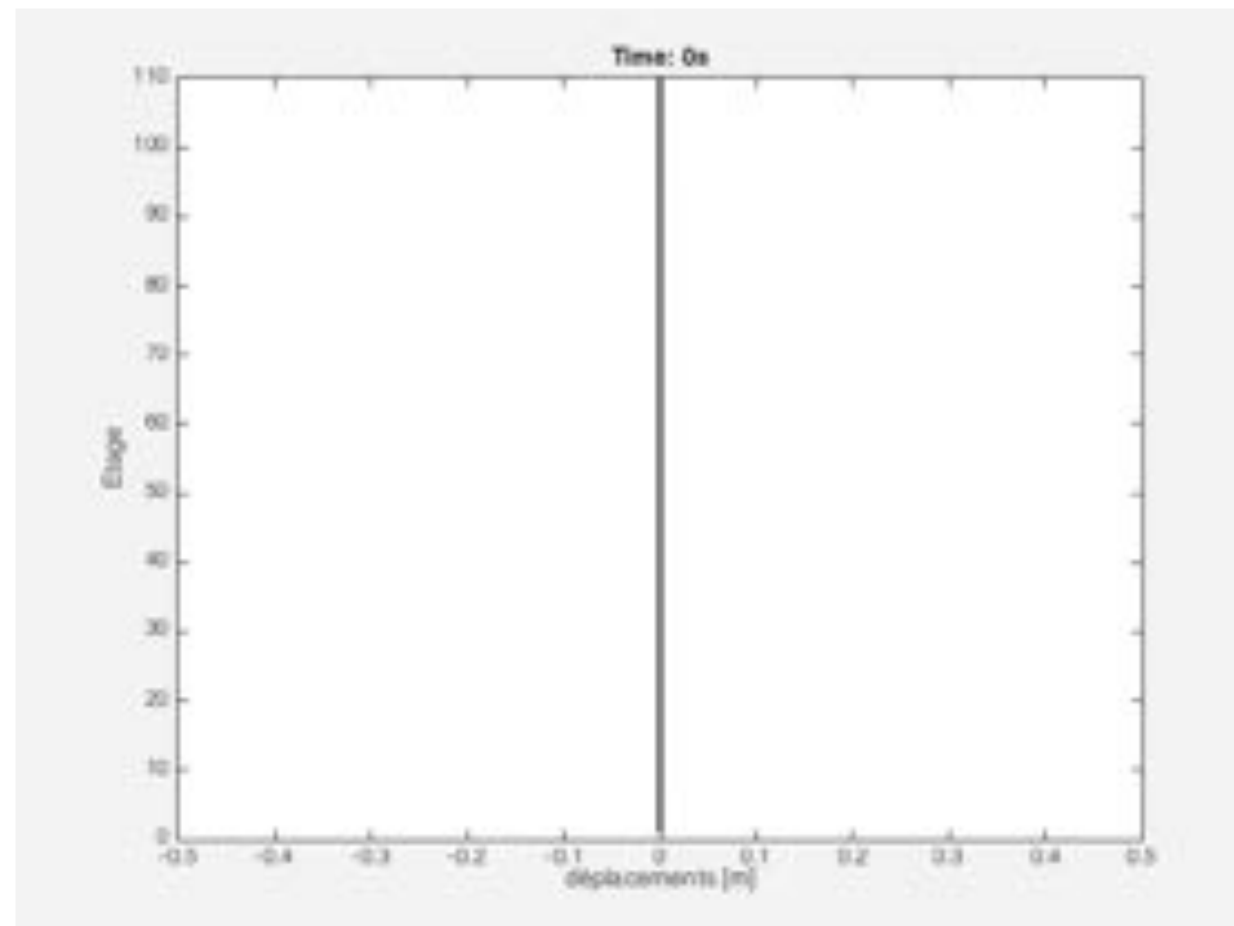
Passive imaging of buildings: SI by deconvolution

Model

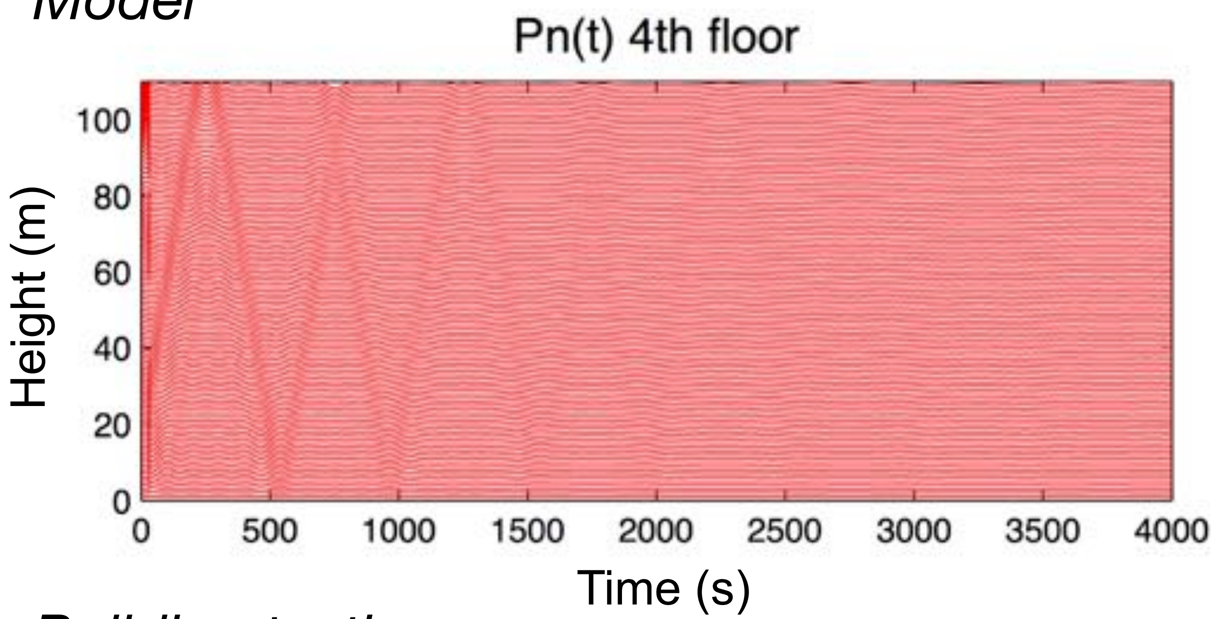


$$h(t) = \frac{1}{\omega_D m} e^{-\zeta \omega t} sin(\omega_D t) \qquad t > 0$$



Passive imaging of buildings: SI by deconvolution

Model



$$h(t) = \frac{1}{\omega_D m} e^{-\zeta \omega t} sin(\omega_D t) \qquad t > 0$$

$$D(z, \omega) = \frac{u(z, \omega) u^*(z = \mathrm{H}, \omega)}{|u(z = \mathrm{H}, \omega)|^2 + \varepsilon}$$

$$V_0 = \frac{\Delta_{i,i+1}}{\tau}$$

Building testing

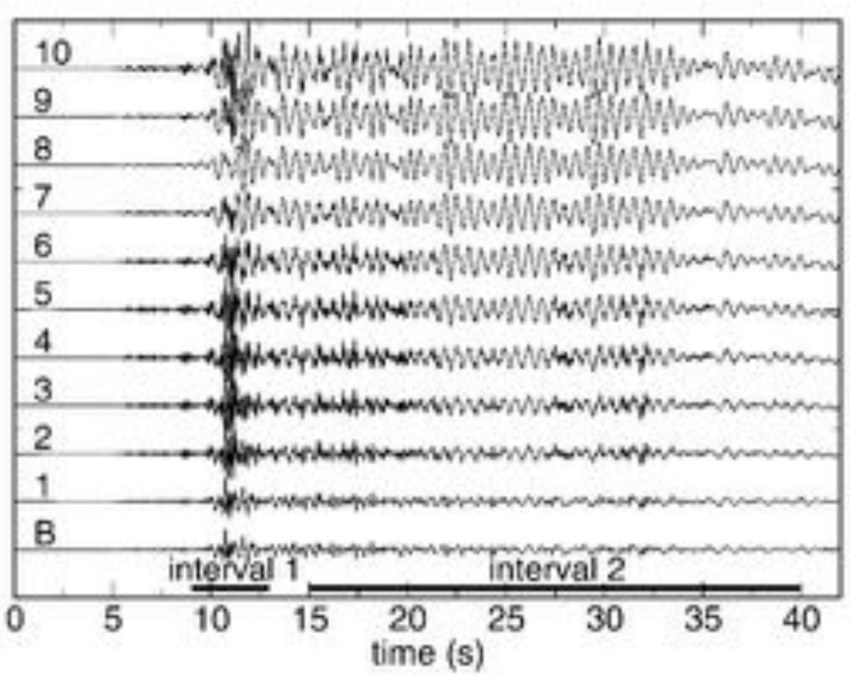


Figure 3. The north–south component of acceleration in the west side of the Millikan Library after the Yorba Linda earthquake of 3 September 2002 (M_L 4.8; time, 02:08:51 PDT; 33.917° N 117.776° W; depth, 3.9 km). The traces are labeled with the floor number (B indicates basement).

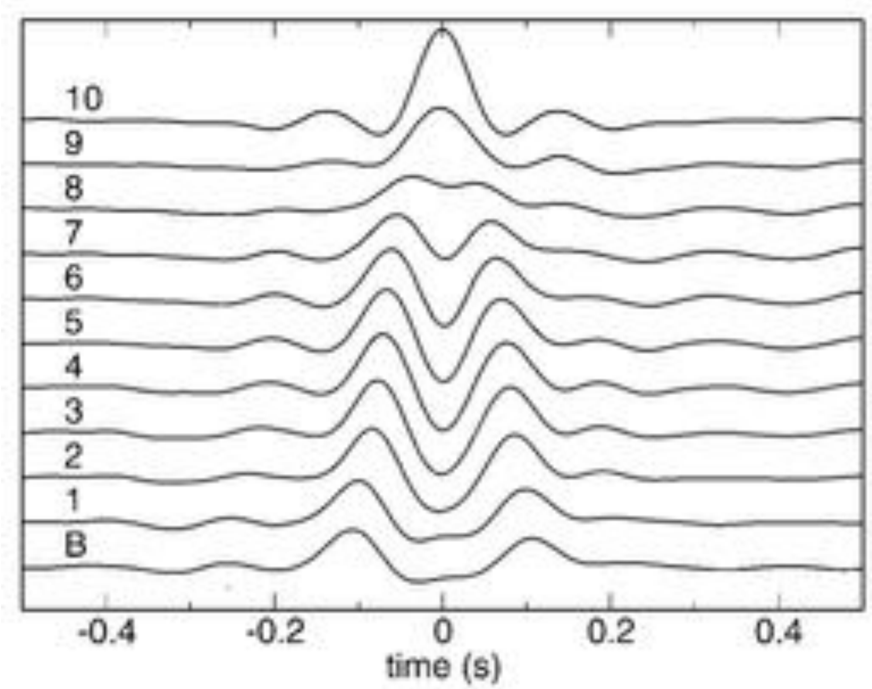


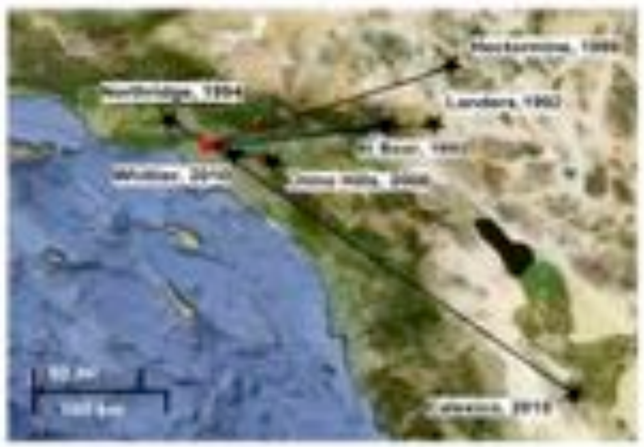
Figure 5. The waveforms of Figure 3 at the different floors after deconvolution with the waves recorded at the top floor.

Snieder and Safak, 2006

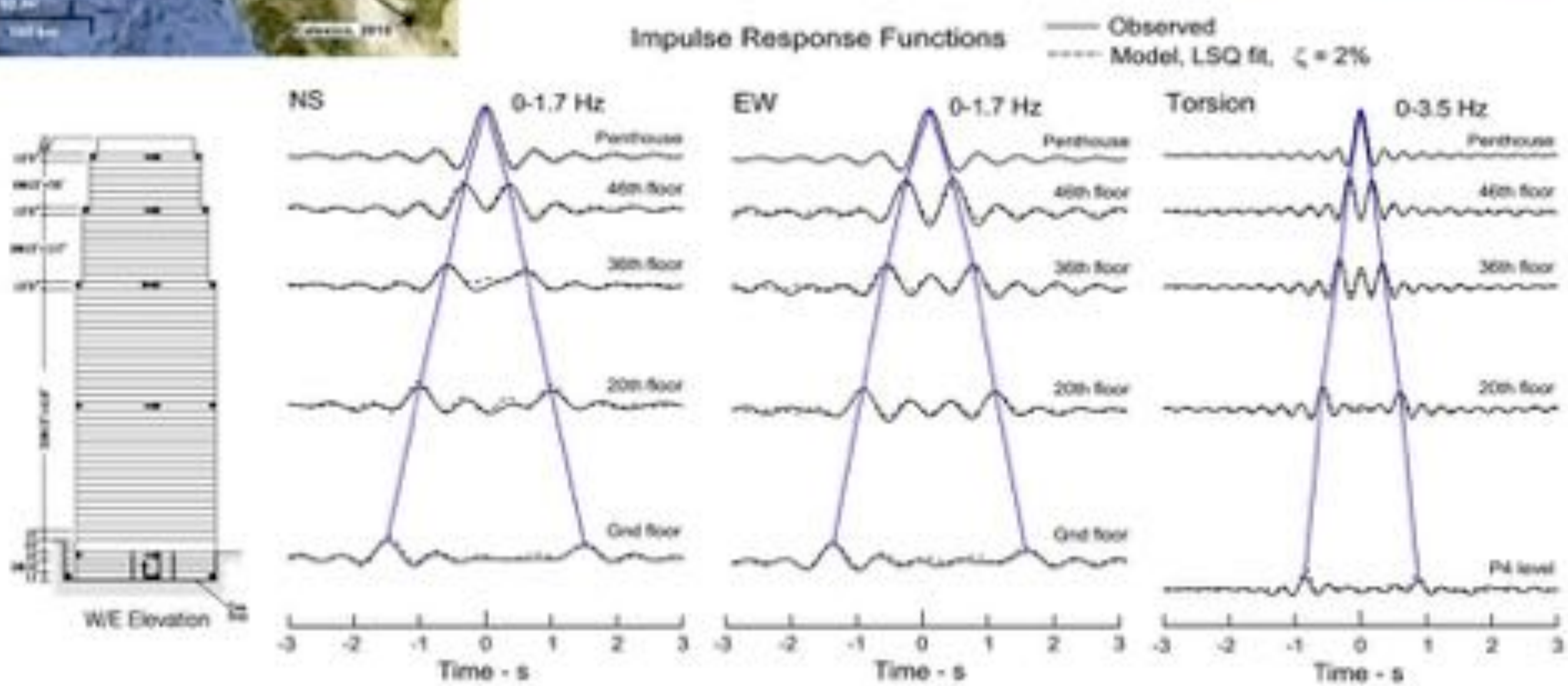
Passive imaging of buildings: SI by deconvolution

LA 54-story office building

54-story, moment resisting **perimeter steel frame**, on concrete mat foundation; alluvium over sedimentary rock



CSMIP Station 24629



Courtesy of M. Todorovska

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Presentation Outline

Non linear seismic response

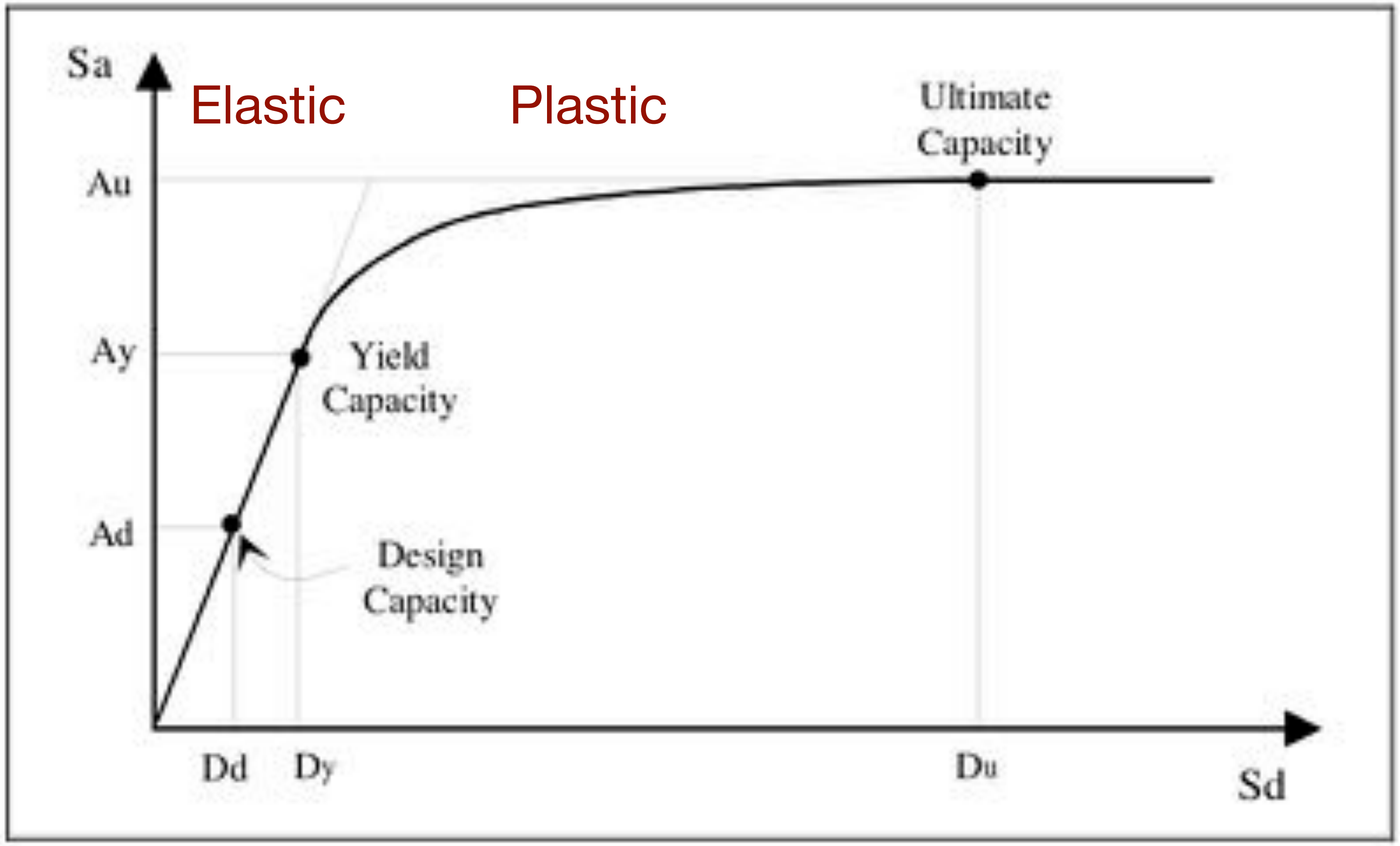
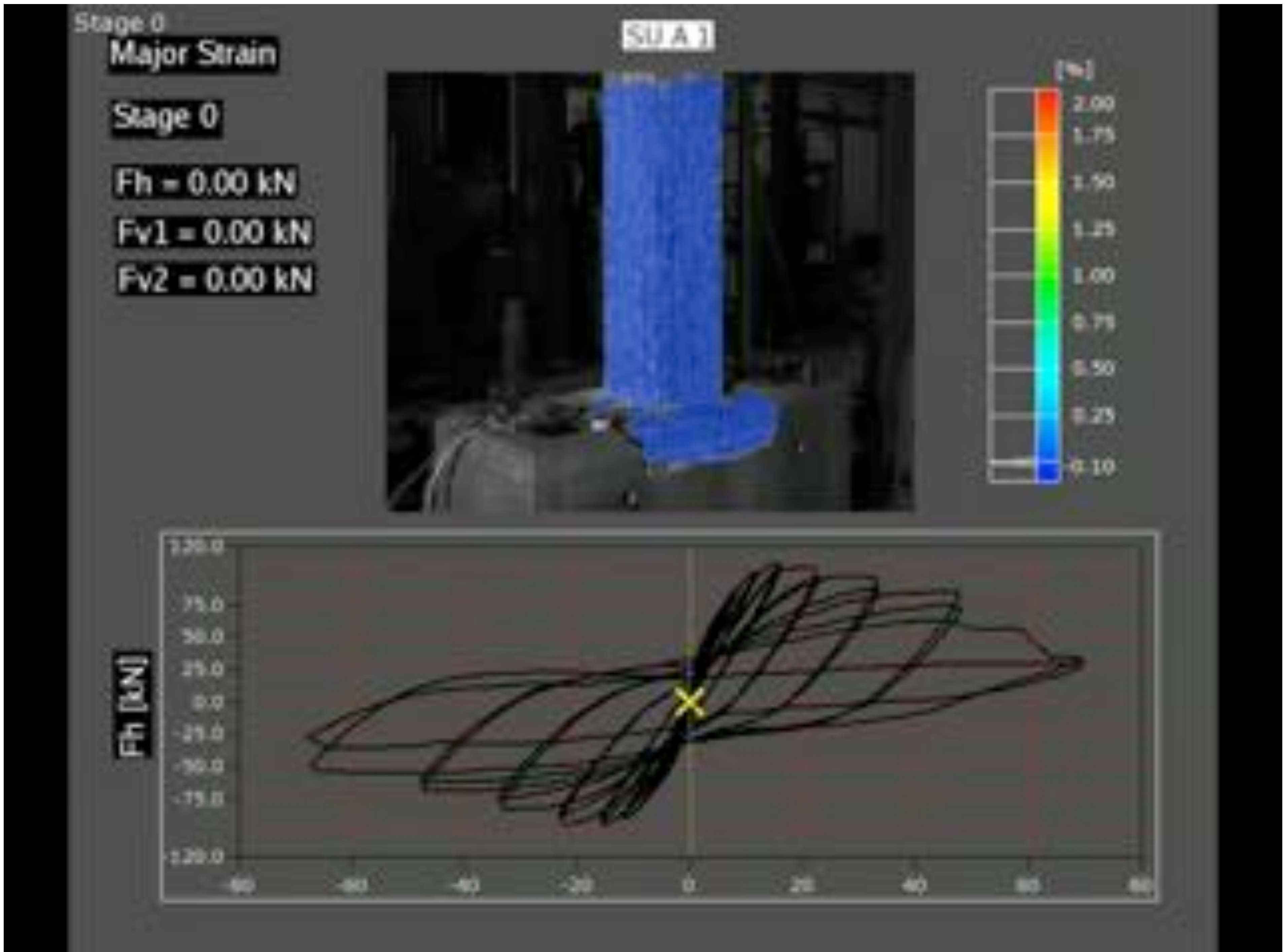


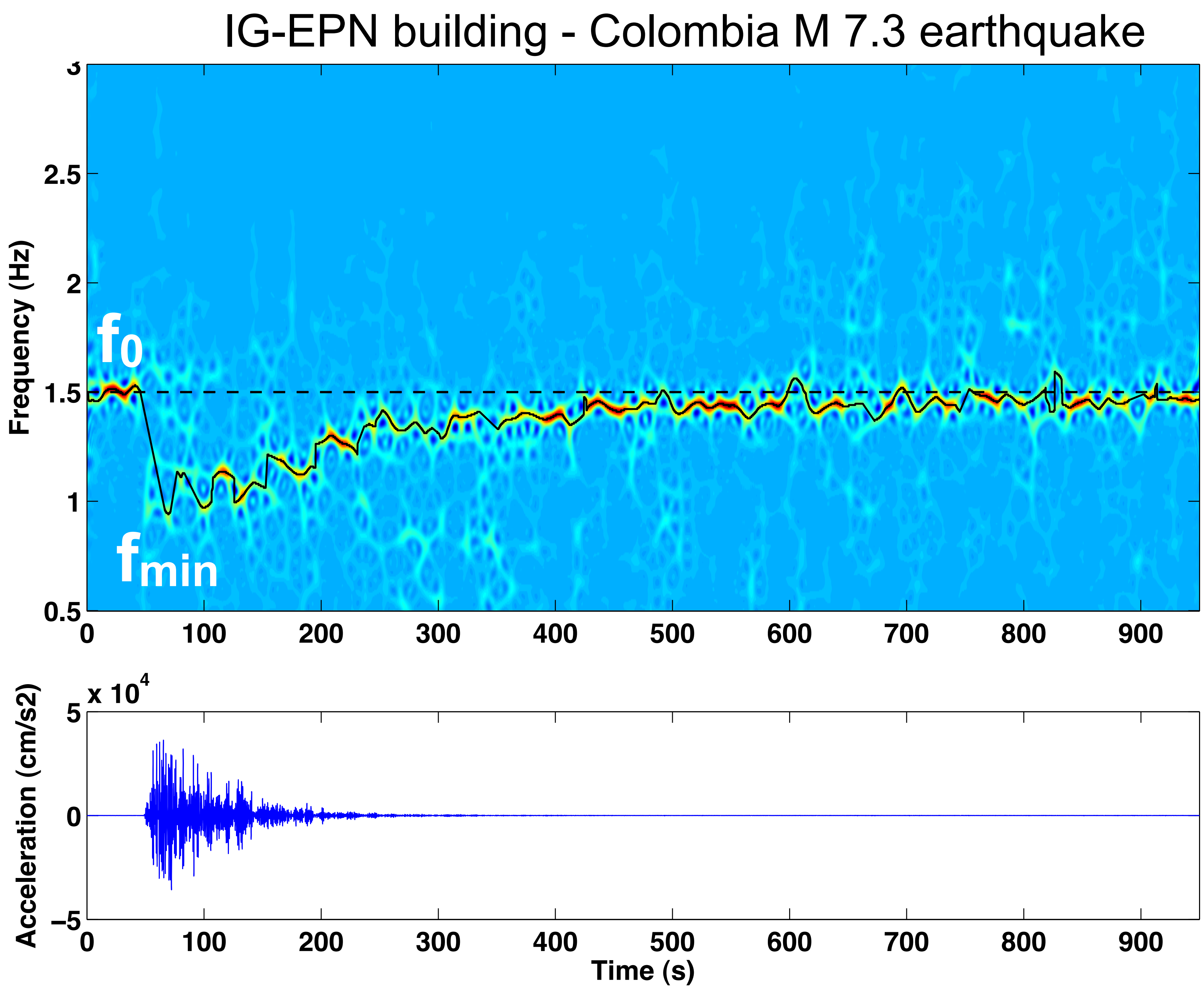
Figure 5.3 Example Building Capacity Curve.

Hazus (US) methods to predict earthquake-based damage:
Dy= $2.10^{-3} - 5.10^{-3}$

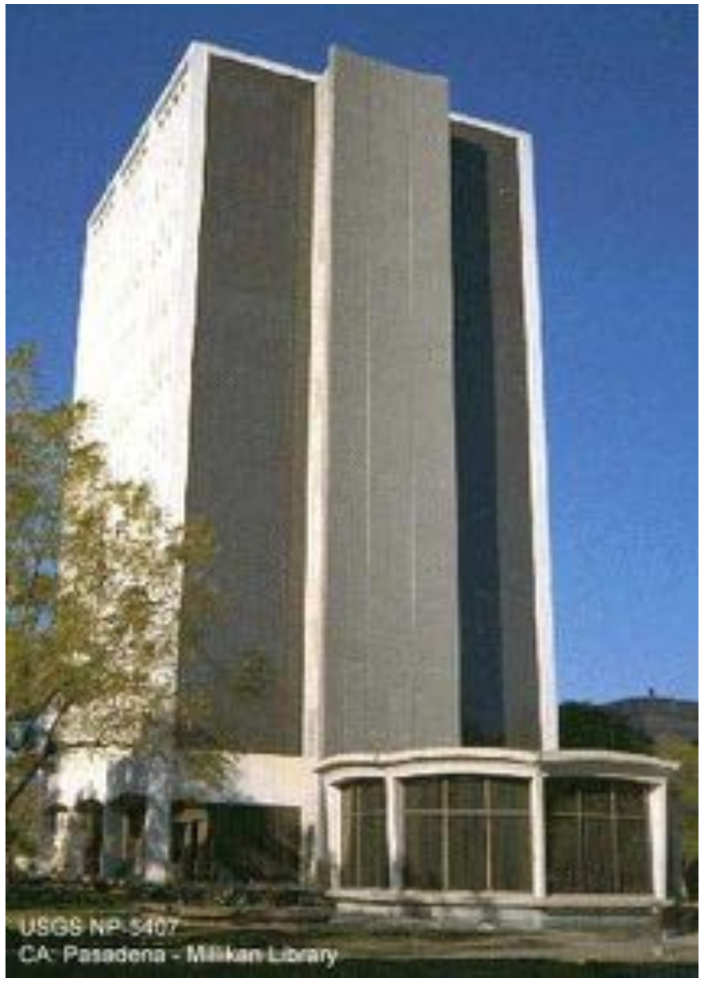
Non linear seismic response

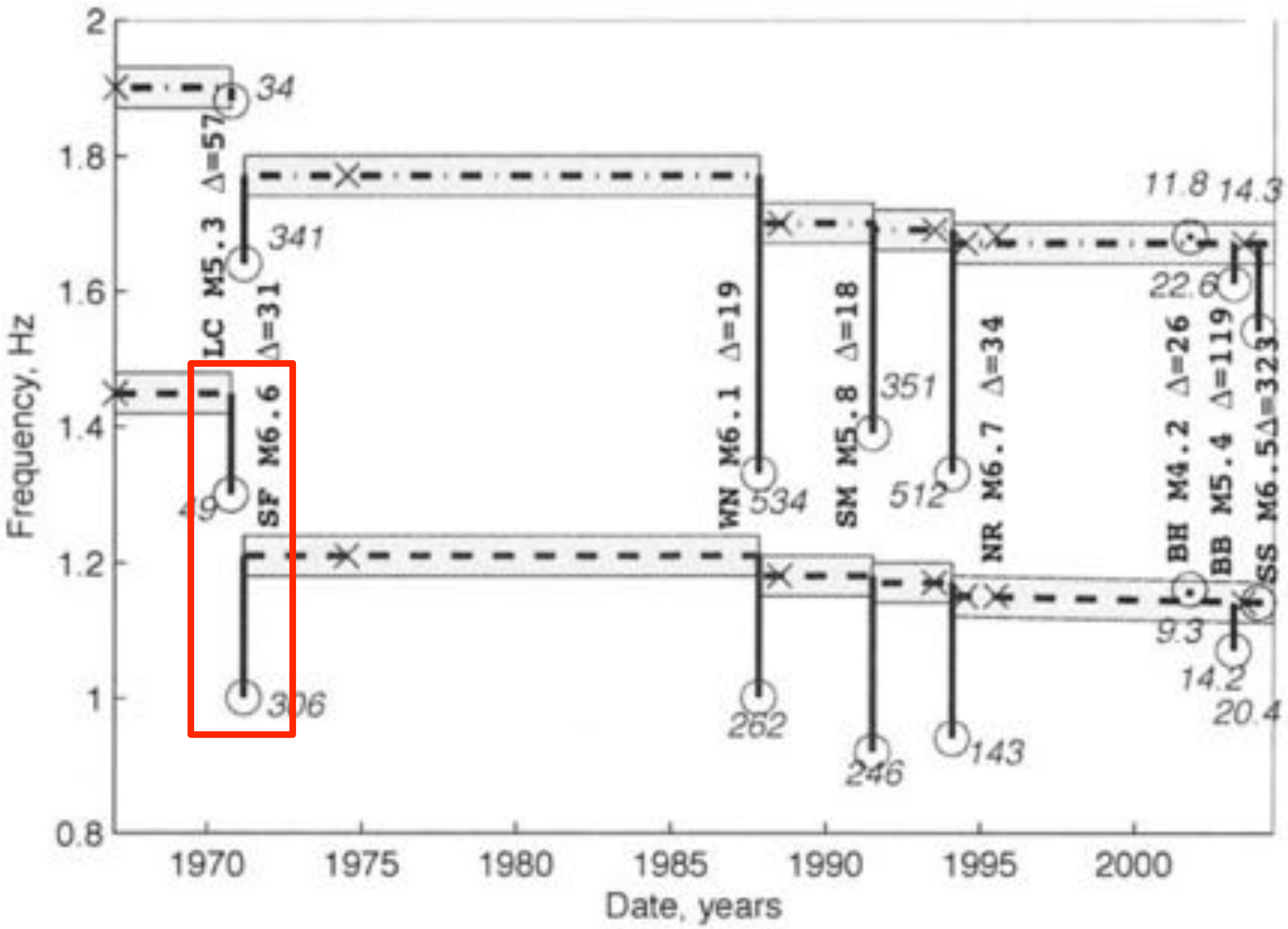


Non linear seismic response



Non linear seismic response



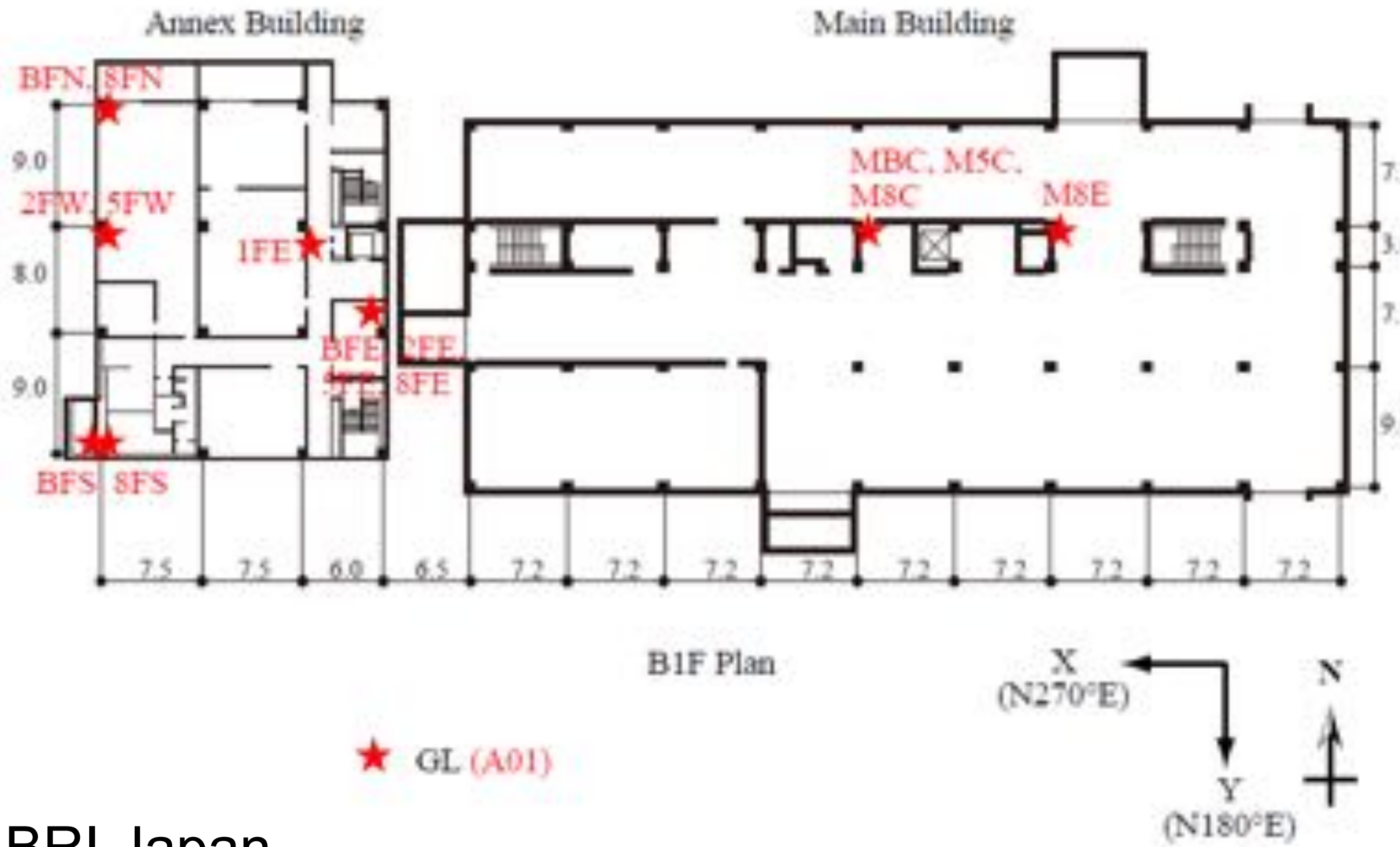


Clinton et al., BSSA, 2006

Non linear seismic response

BRI Annex building

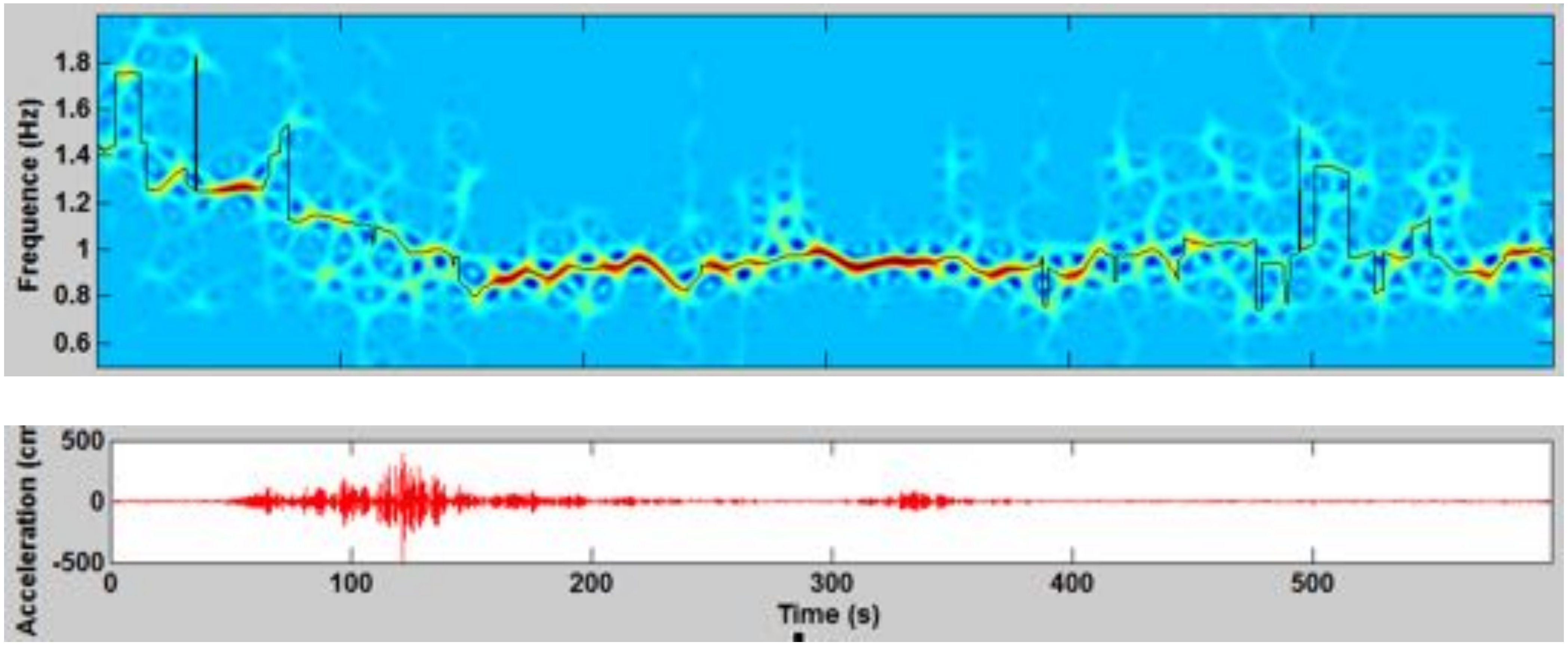
Steel-frame RC Japanese buildings



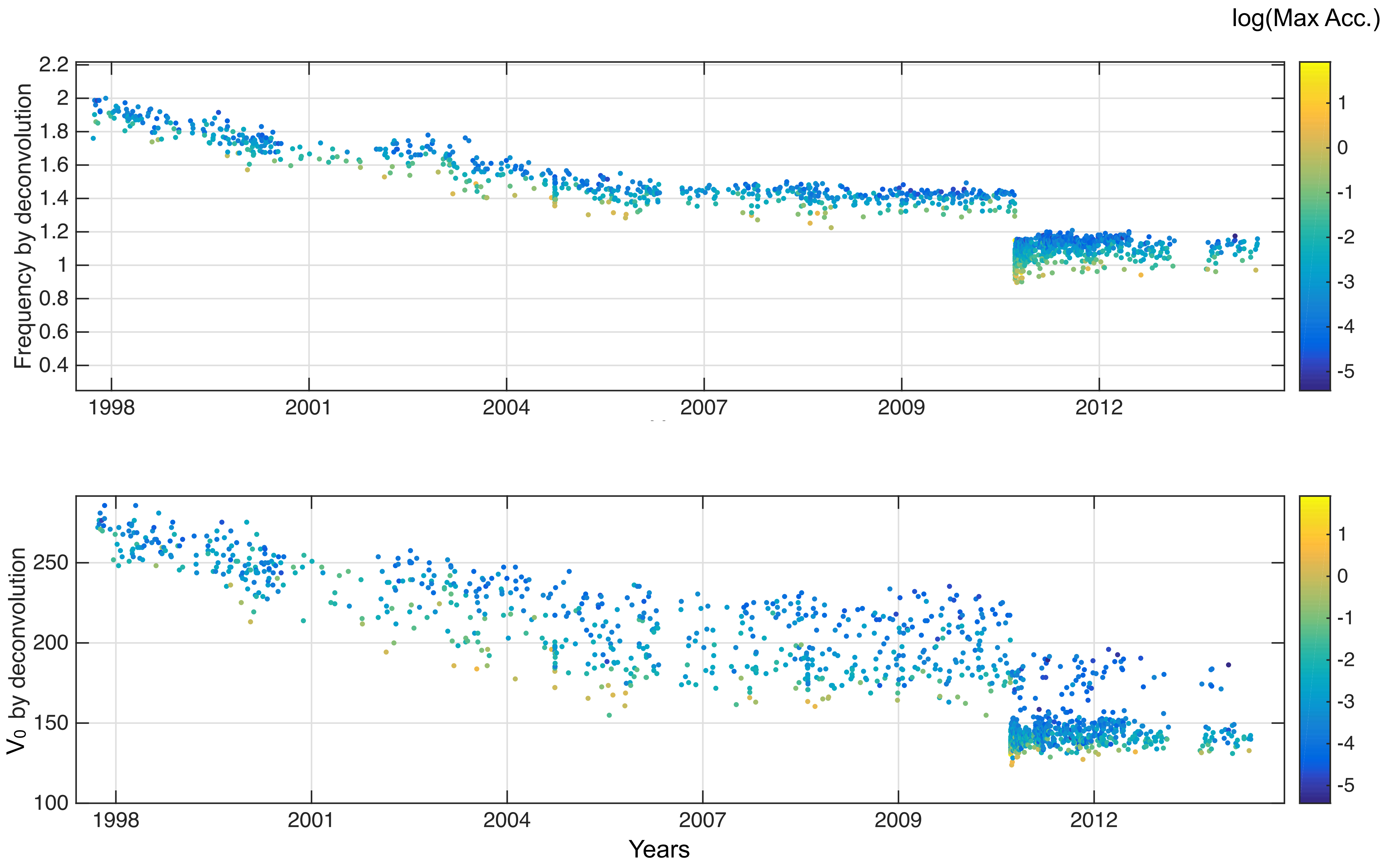
In collaboration with Pr Kashima BRI Japan

Non linear seismic response

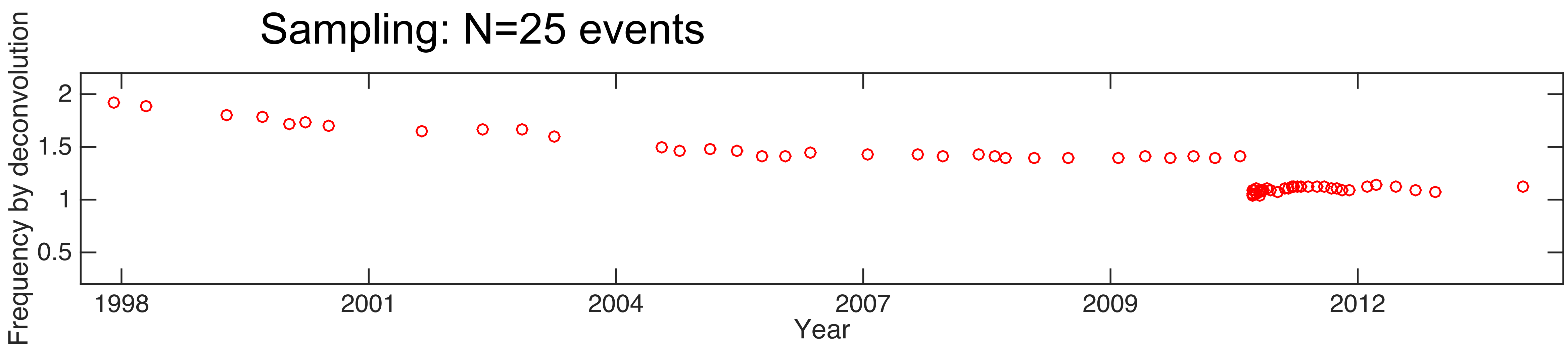
Tohoku earthquake



Non linear seismic response

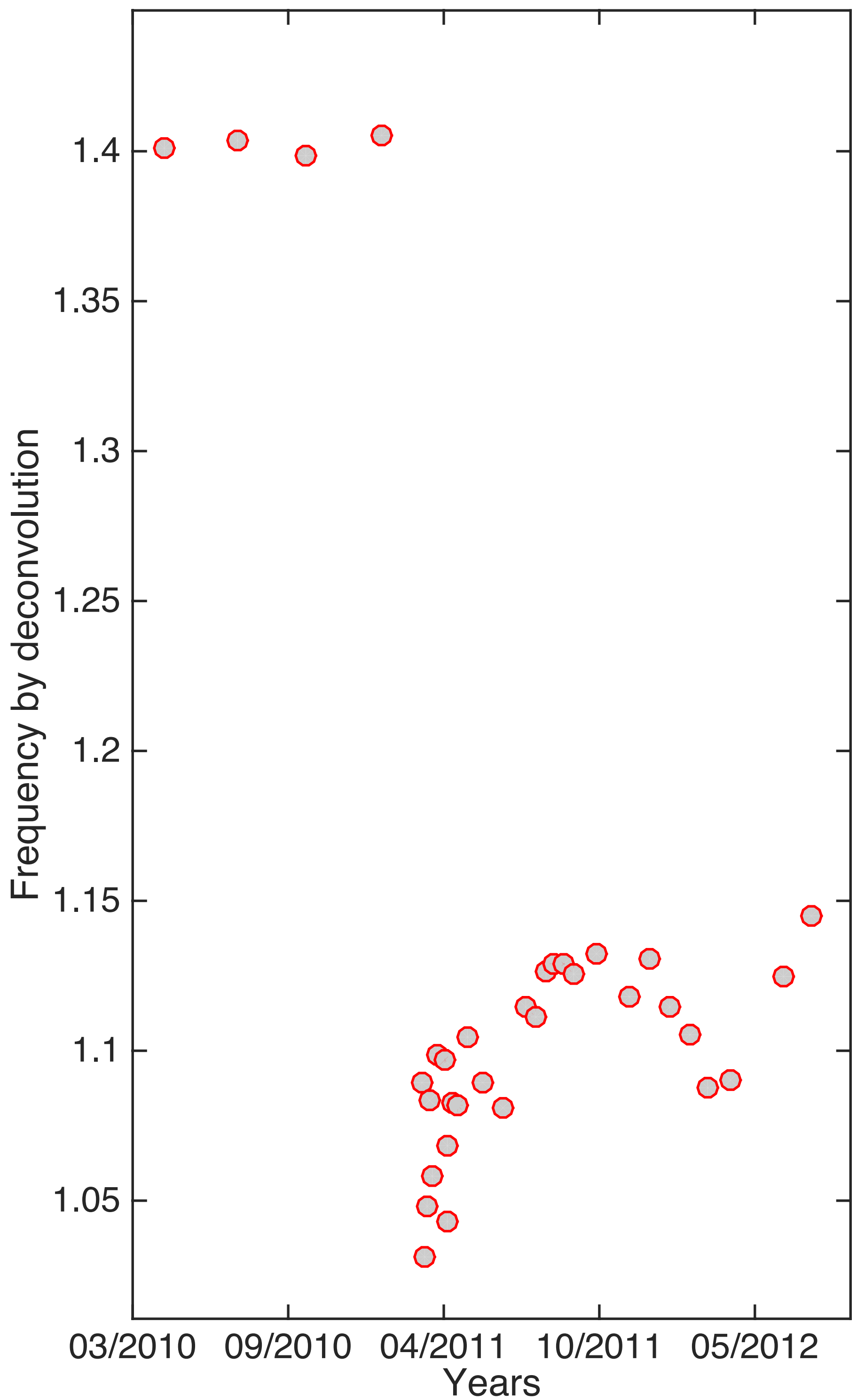


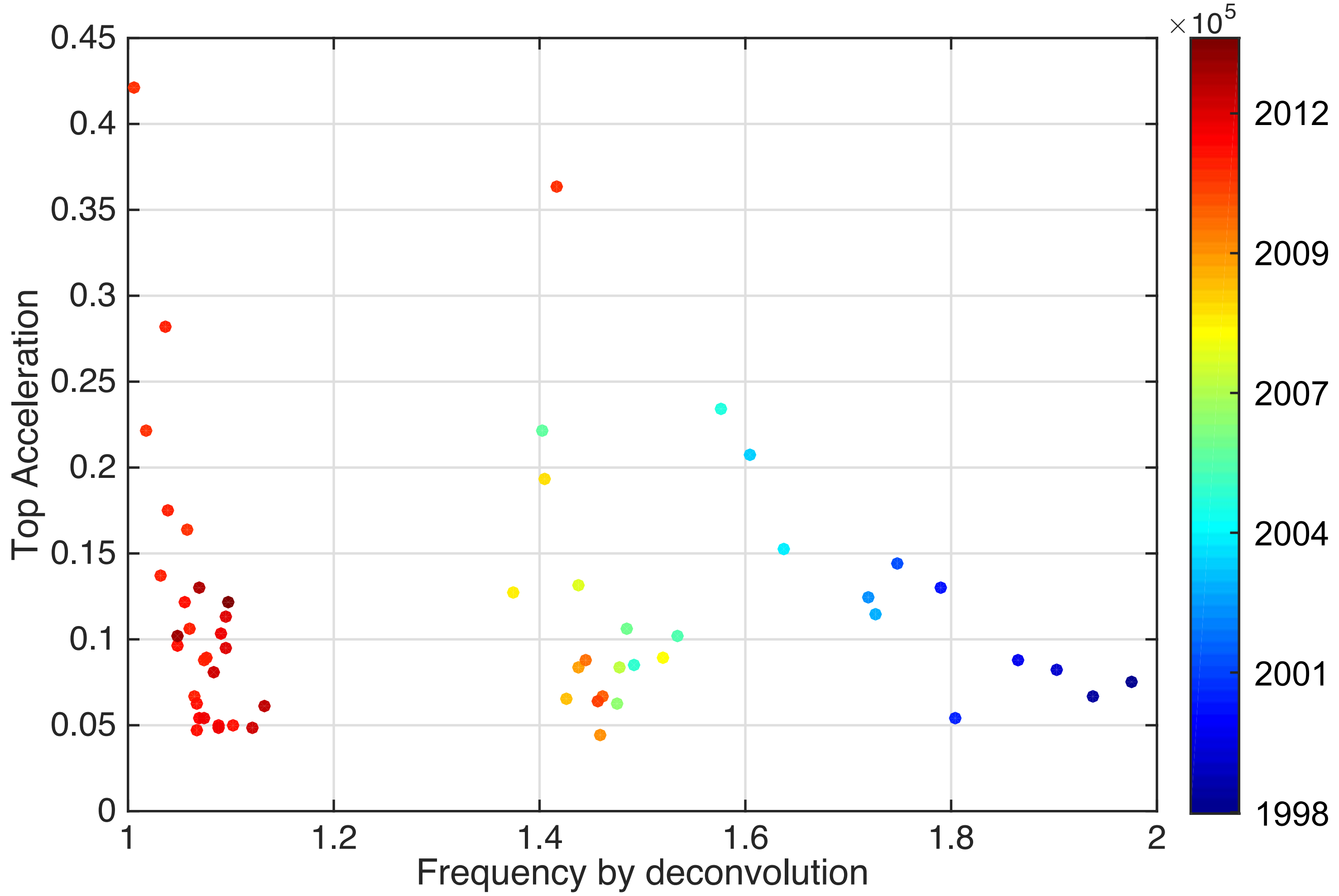
Non linear seismic response



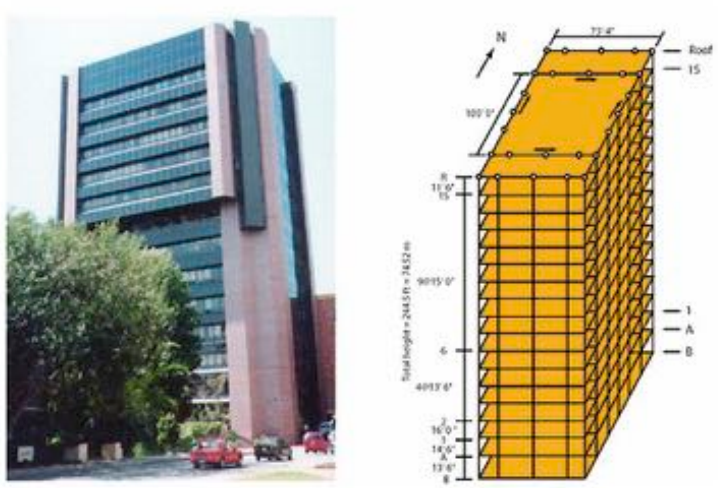
Non linear seismic response

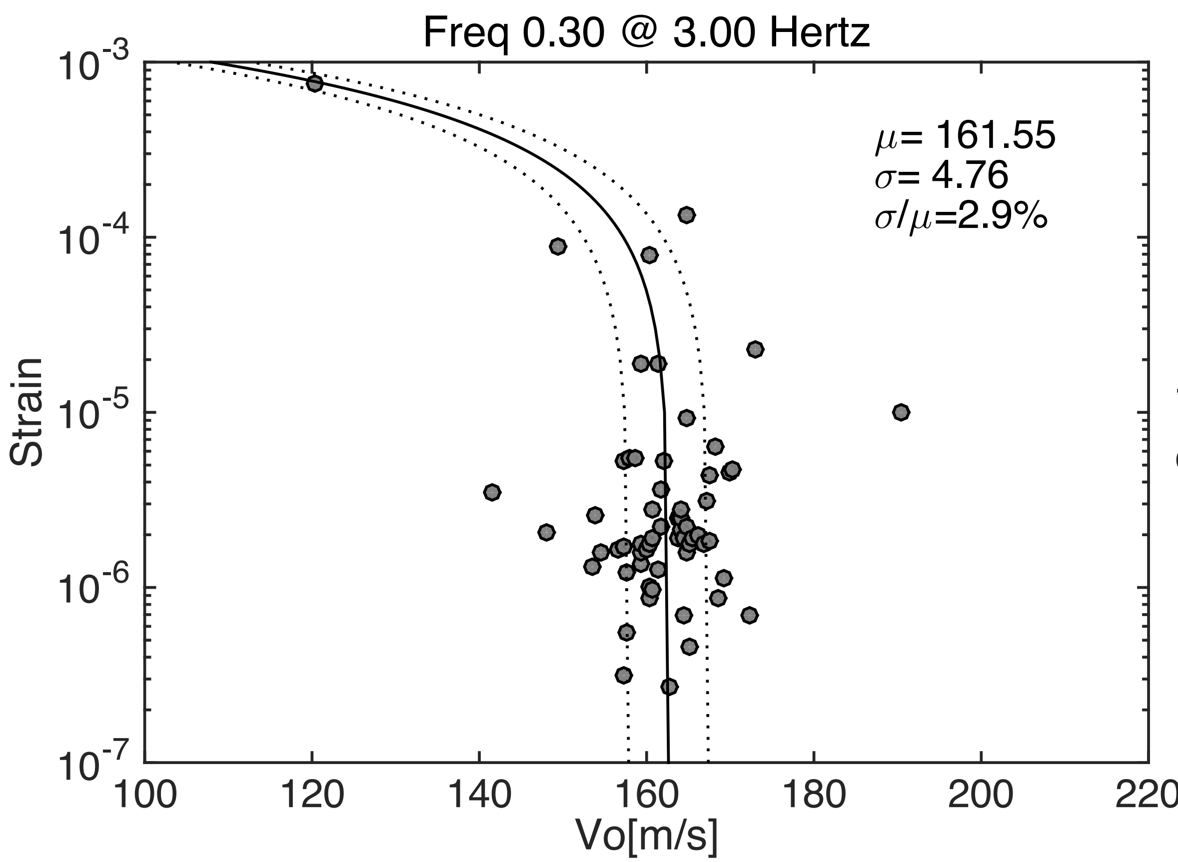
Sampling: N=25 events

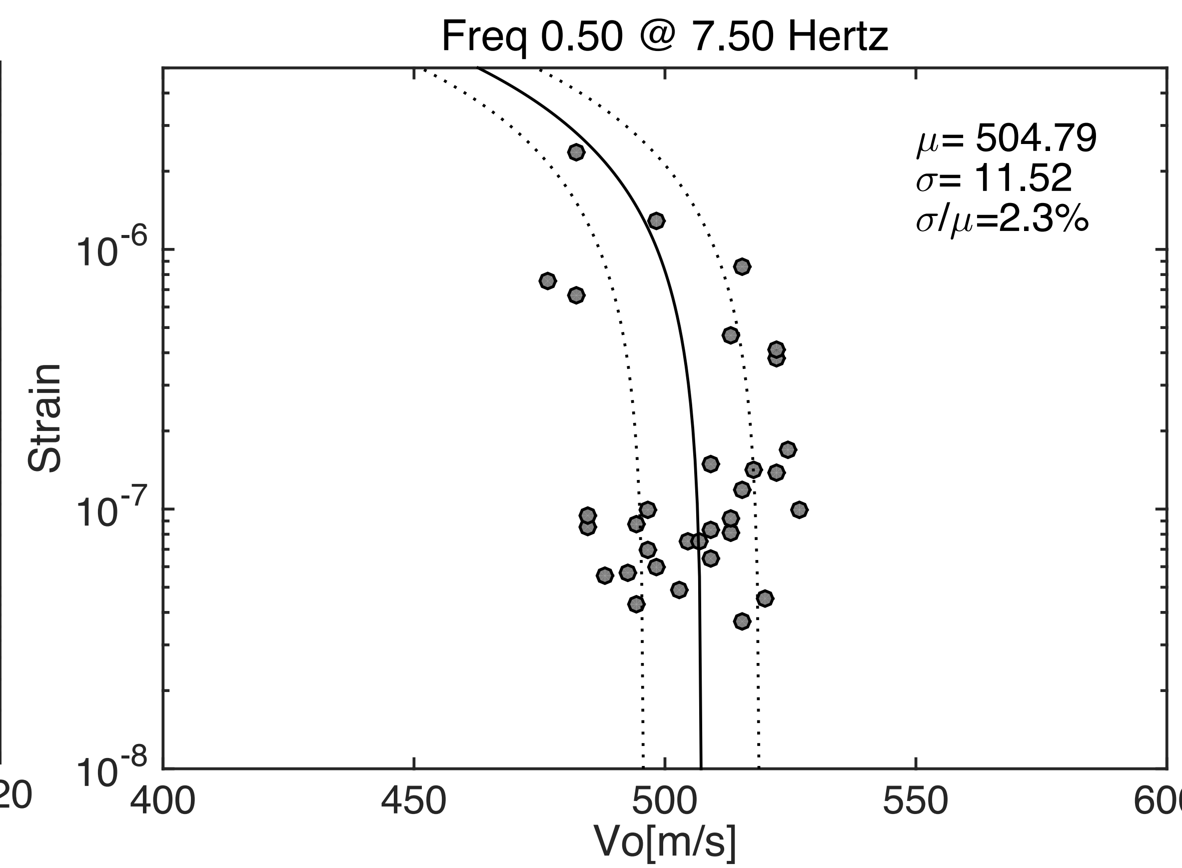




Non linear seismic response







Michel et al., EESD, submitted

Presentation Outline

Part 1: Motivation

Part 2: Structural Dynamics

Part 3: How to we get the dynamic properties ?

Part 4: Passive imaging of buildings

Part 5: Non-linear seismic response of buildings

Part 6: Natural wandering and nonlinear elasticity

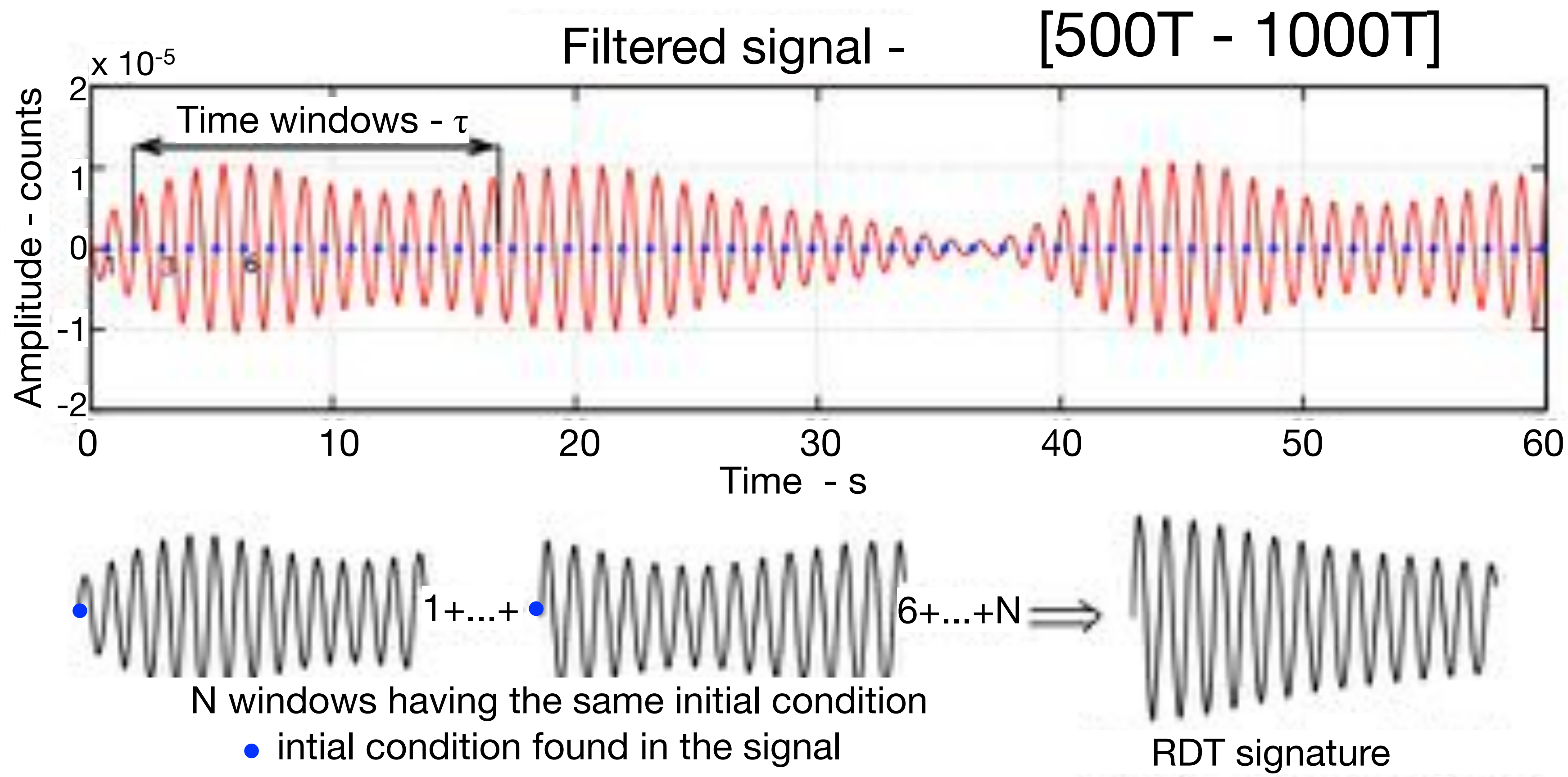
Natural wandering

Random Decrement Technique RDT

stationnary and white noise conditions of ambient vibrations

To stack a large number of short windows having the same triggering condition

Mikael et al., BSSA, 2013

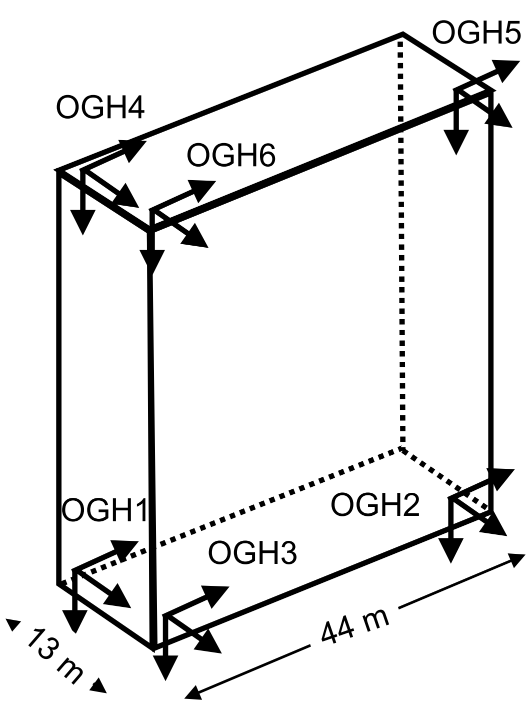


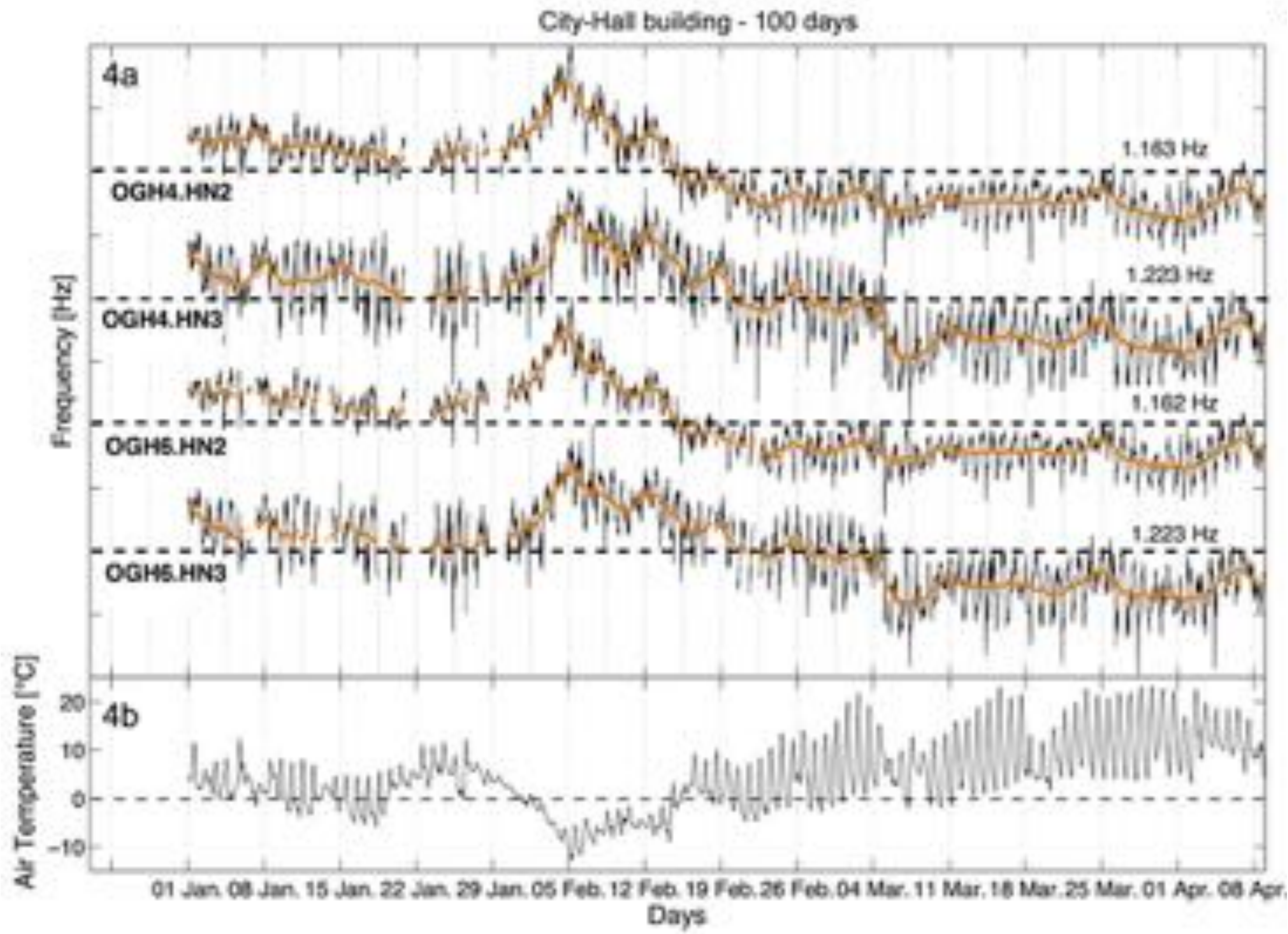
$$RDT(\tau) = \frac{1}{N}\sum_{i=1}^{N} s(t_i + \tau)$$

- Band-pass filtering Butterworth (order 4)
  [f1 - f2] at ΔA > 3dB
- N windows <=> 500-1000 T - 20 minutes
- τ= 10T - 5 secondes
- Triggering conditions: v(t)=0, u(t)>0

Mikael et al., BSSA, 2013

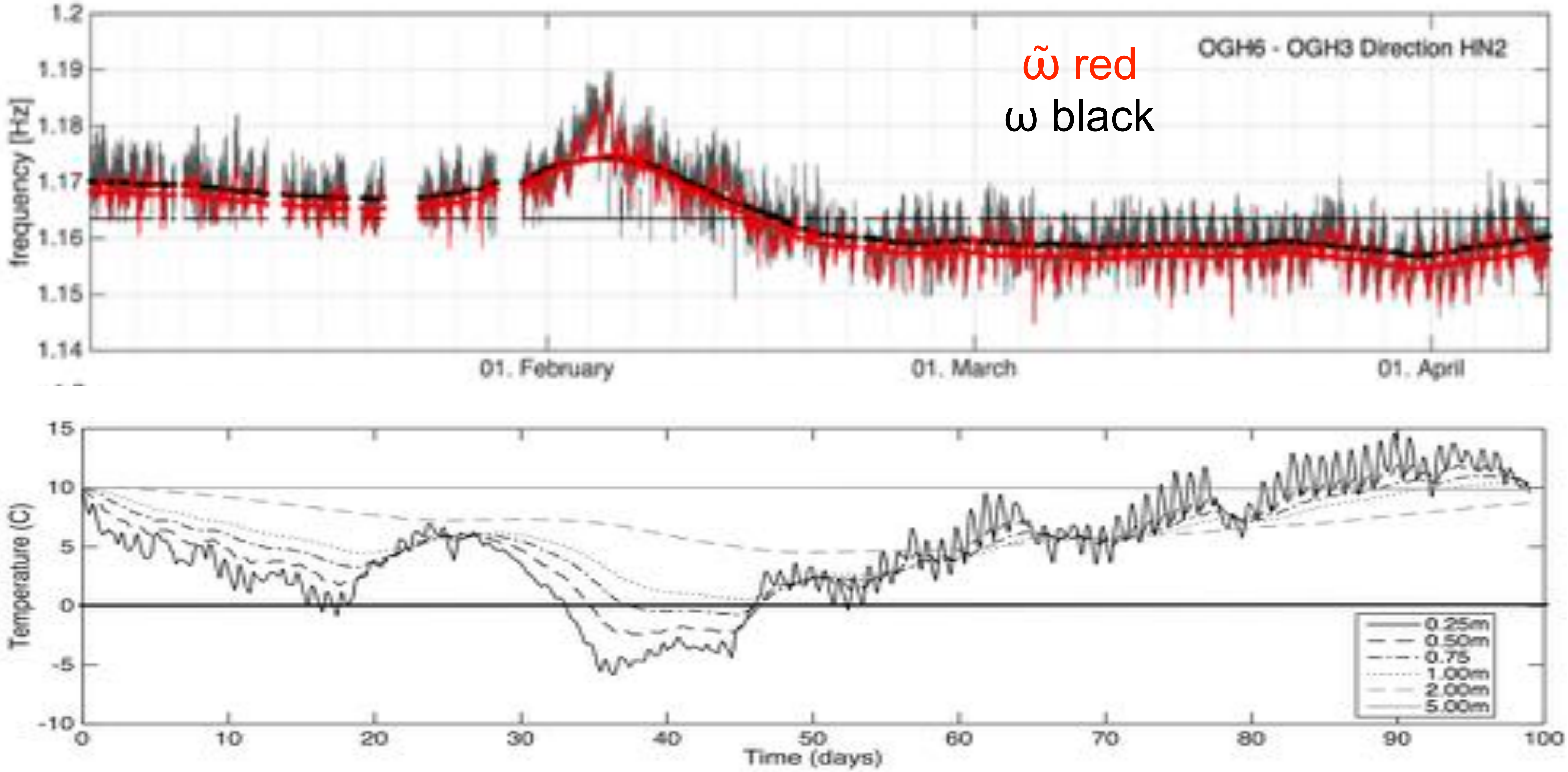
Natural wandering: example 1 City Hall Grenoble





Guéguen et al.,SCHM, submitted

Natural wandering: example 1 City Hall Grenoble



$$\frac{1}{\widetilde{\omega}^2} = \frac{1}{\omega_0^2} + \frac{1}{\omega_1^2} + \frac{1}{\omega_\theta^2}$$

Guéguen et al.,SCHM, submitted

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Natural wandering: example 2 Anne Paul building

The Anne Paul's buildings

location:

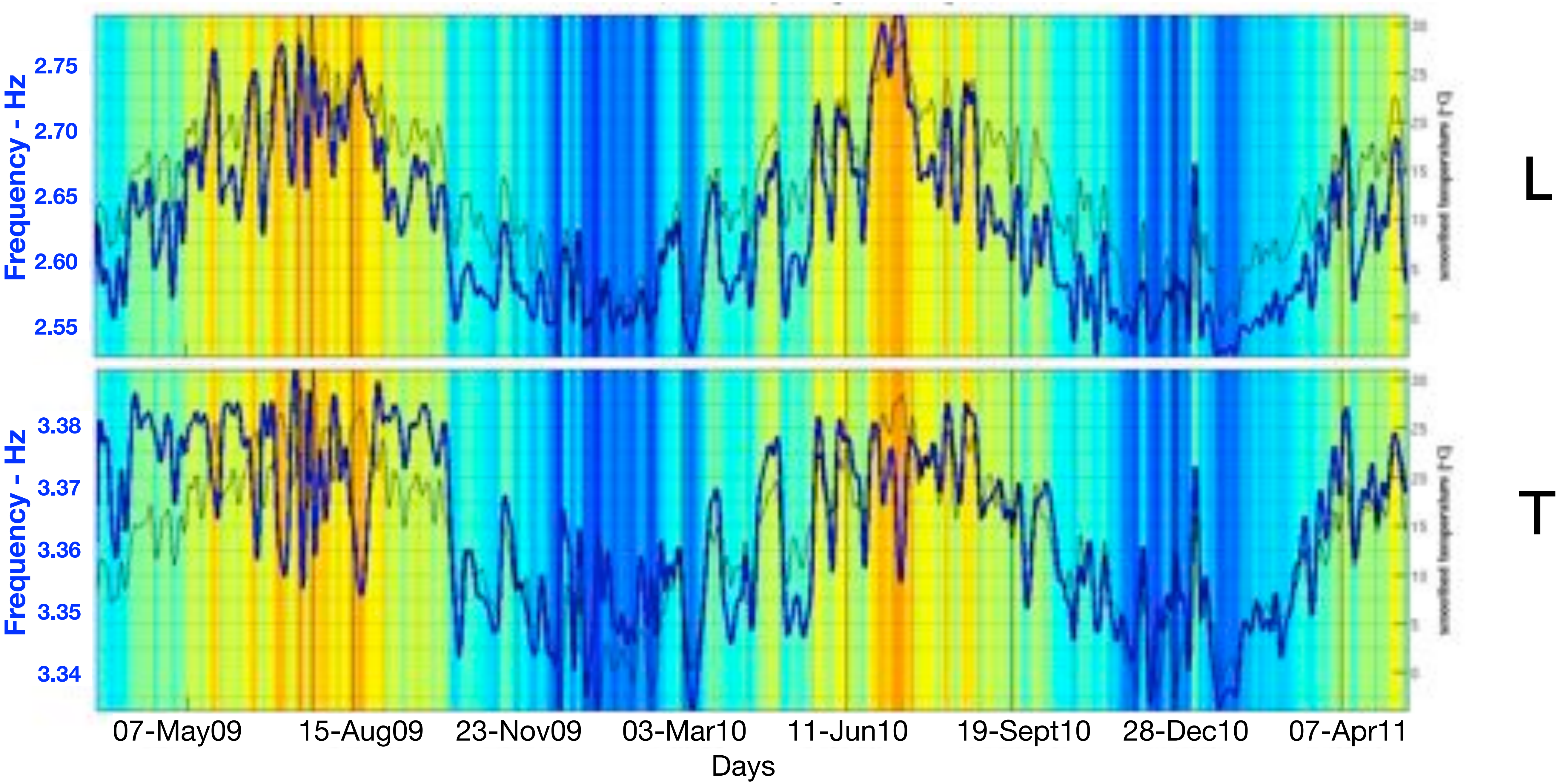
23 avenue Alsace-Lorraine – 38000 GRENOBLE (7eme étage)

recording period :

12/03/2009 – 17/05/2011

Natural wandering: example 2 Anne Paul building

Quasi-static events: environmental loading



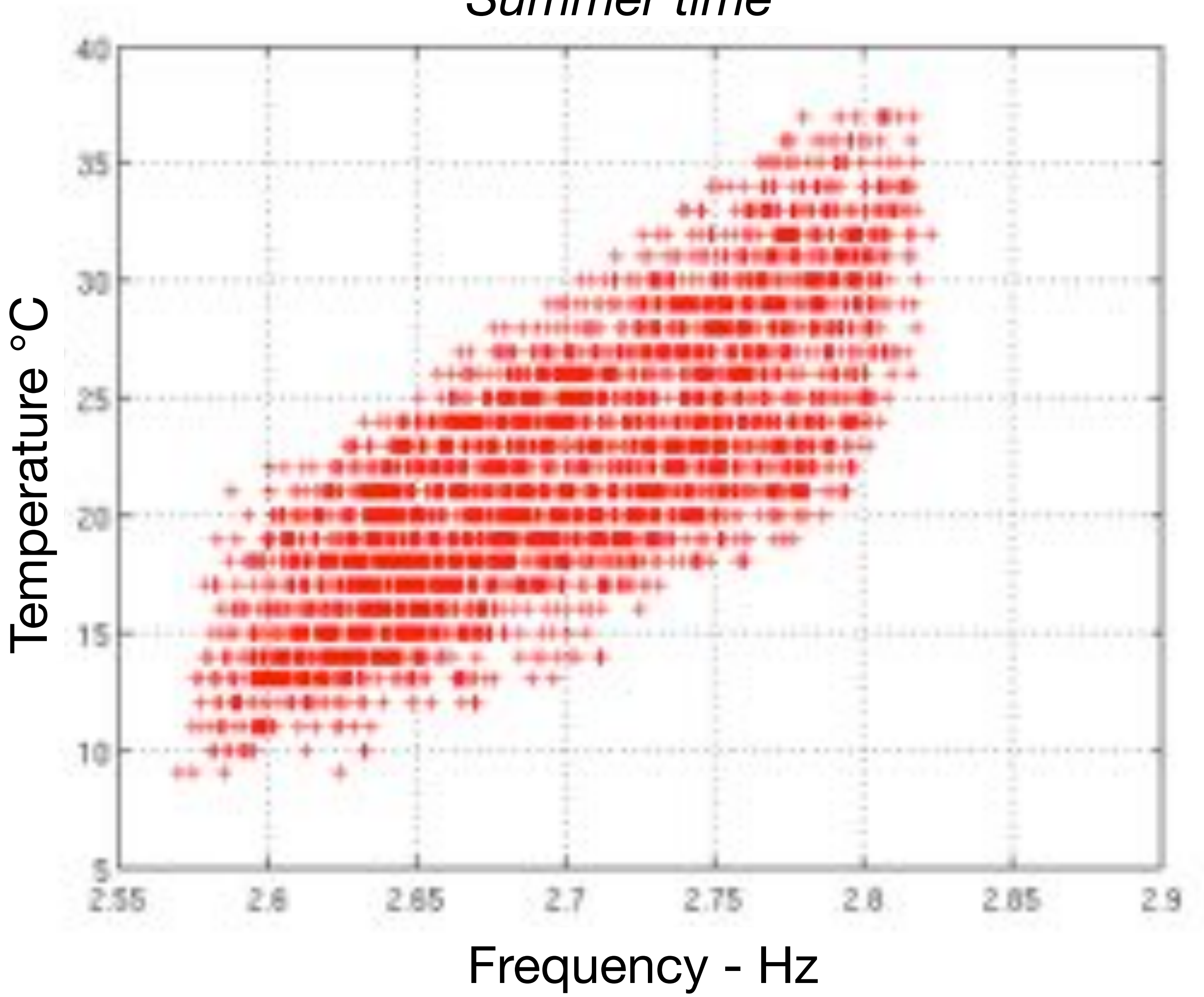
Δf +/-4% L

Δf +/-0.6 T

Natural wandering: nonlinear elasticity

Non-linear elasticity of building response to slow loading

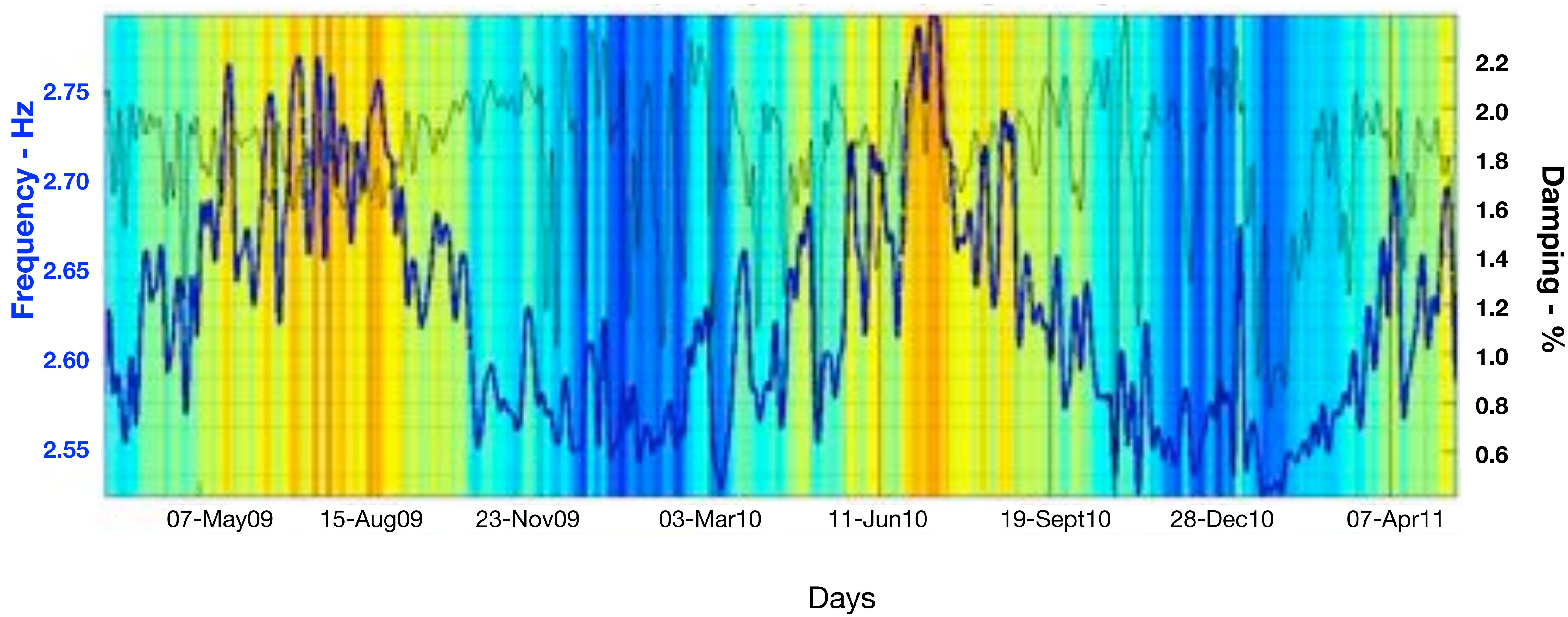
Summer time



Natural wandering: example 2 Anne Paul building

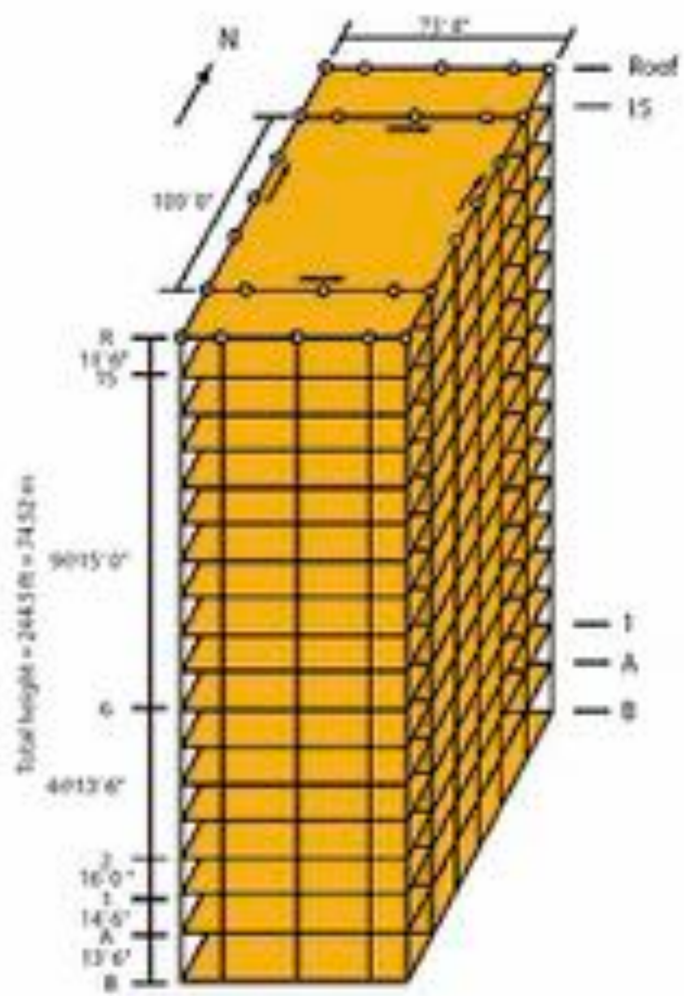
Quasi-static events: environmental loading

Long-term (seasonal) variations - Smoothed with a sliding windows of 120 hours length



Natural wandering: example 3 factor Building (CA)

Factor building (IRIS web service)

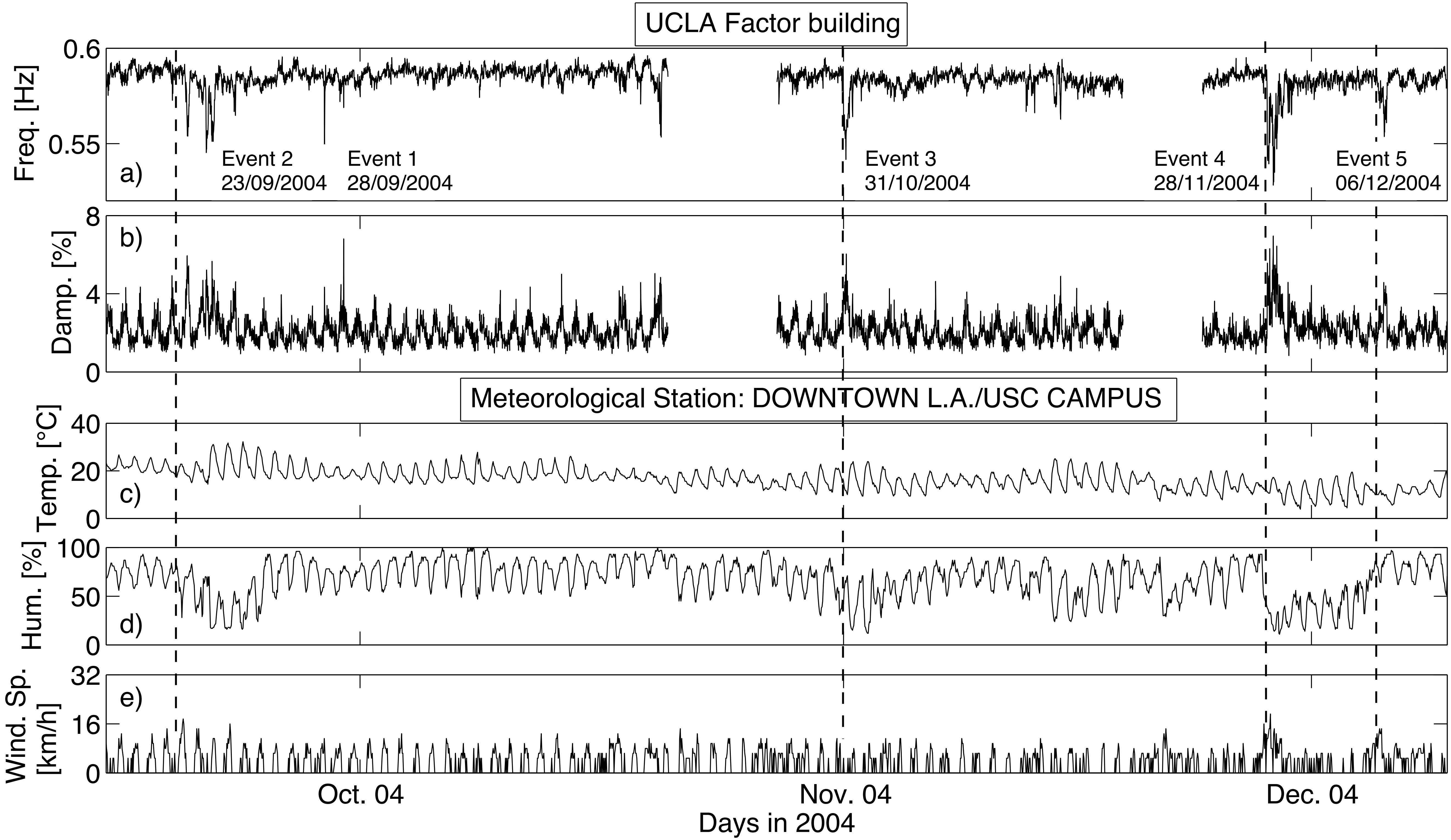


Data from Sept. to Dec. 2004

2004/09/28 - Parkfield Earthquake
Mw=6.0
200 km far from the building

Top and bottom recordings

$$Strain = max\left[\frac{U_{top}(t) - U_{bot}(t)}{H}\right]$$



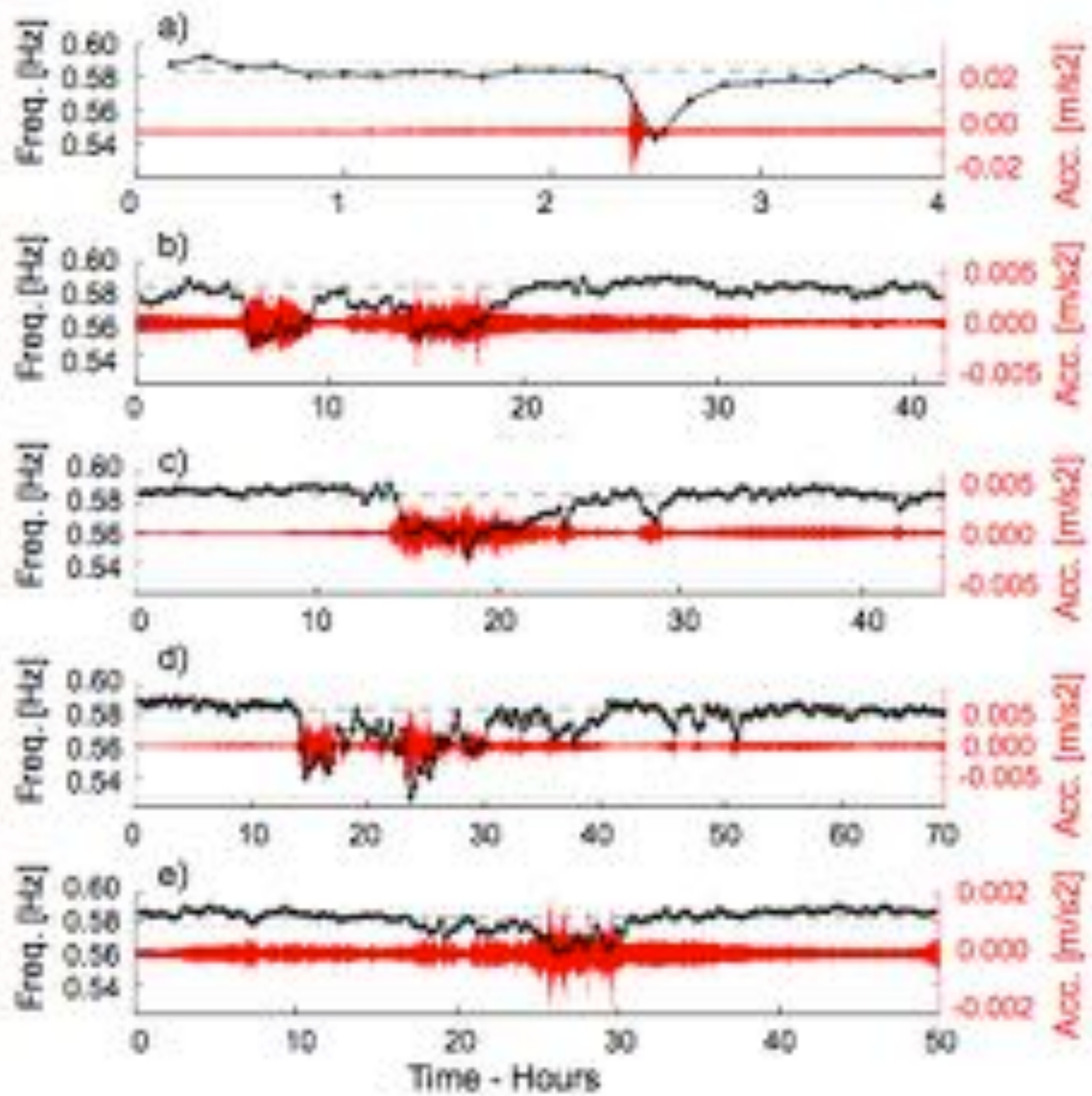
Dynamic - Event 1 - 2004/09/28 - Parkfield Earthquake Mw=6.0 - R=200 km

Static - Events 2 to 5 - Elastic variation controlled by atmospheric conditions

Clinton et al., BSSA, 2006; Todorovska and Al Rjoub, SDEE, 2006; Todorovska, BSSA, 2009; Mikael et al., BSSA 2013

Guéguen, Johnson, Roux, will be published next decade

Natural wandering: example 3 factor Building (CA)



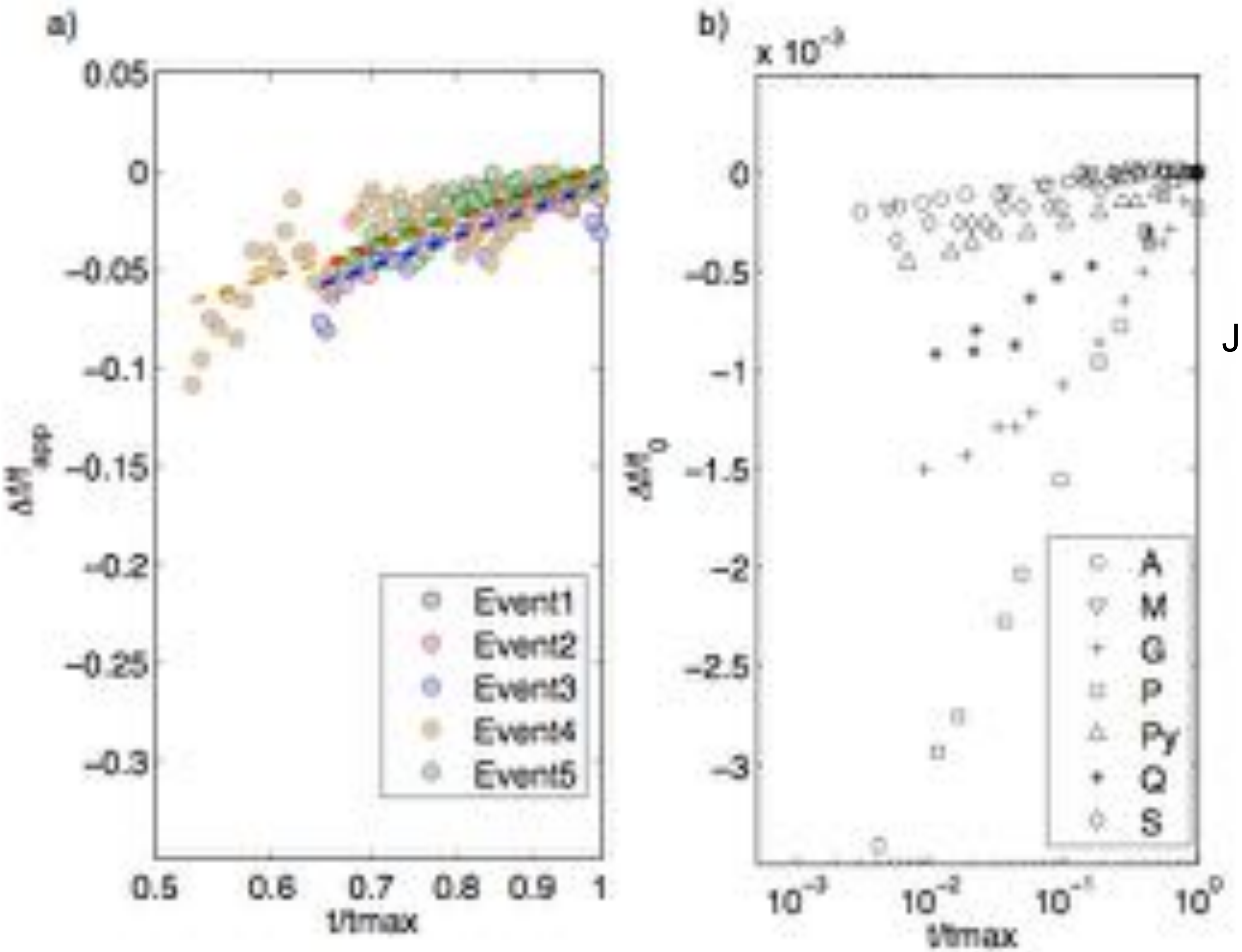
Dynamic Event
Event 1
Top disp: 2 mm
Drift: 3 10^{-5}

Static Event
Event 3
Top Disp: 0.5 mm
Drift: 4 10^{-6}

Guéguen, Johnson, Roux, will be published next decade

Natural wandering: example 3 factor Building (CA)

Nonlinear elasticity at Factor building compared to laboratory scale results



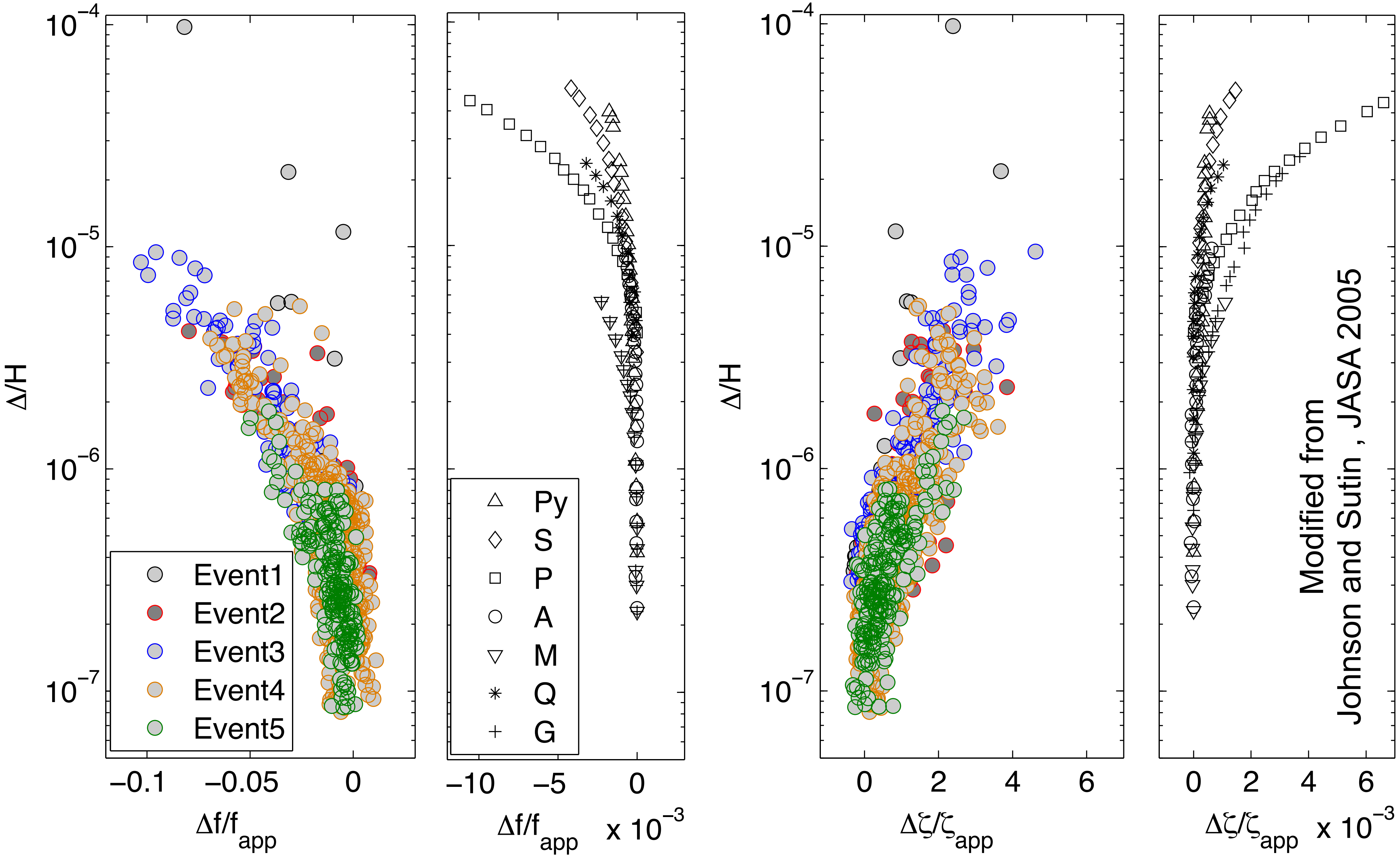
Modified from
Johnson and Sutin , JASA 2005

Hazus : Yield capacity Dy=2.10 $^{-3}$ - 5.10^{-3}

Guéguen, Johnson, Roux, will be published next decade

Natural wandering: example 3 factor Building (CA)

Nonlinear elasticity at Factor building compared to laboratory scale results



Hazus : Yield capacity Dy=2.10 $^{-3}$ - 5.10^{-3}

Guéguen, Johnson, Roux, will be published next decade

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Conclusions

Building testing thanks to new instrumentation

- physical origin of frequencies and damping in actual buildings
- for SHM and CBM

NL elasticity and slow dynamic

- probing the invariant scale of NL elasticity
  (laboratory mm *Johnson*, building m, earth km *Brenguier*)

- related to the structural health